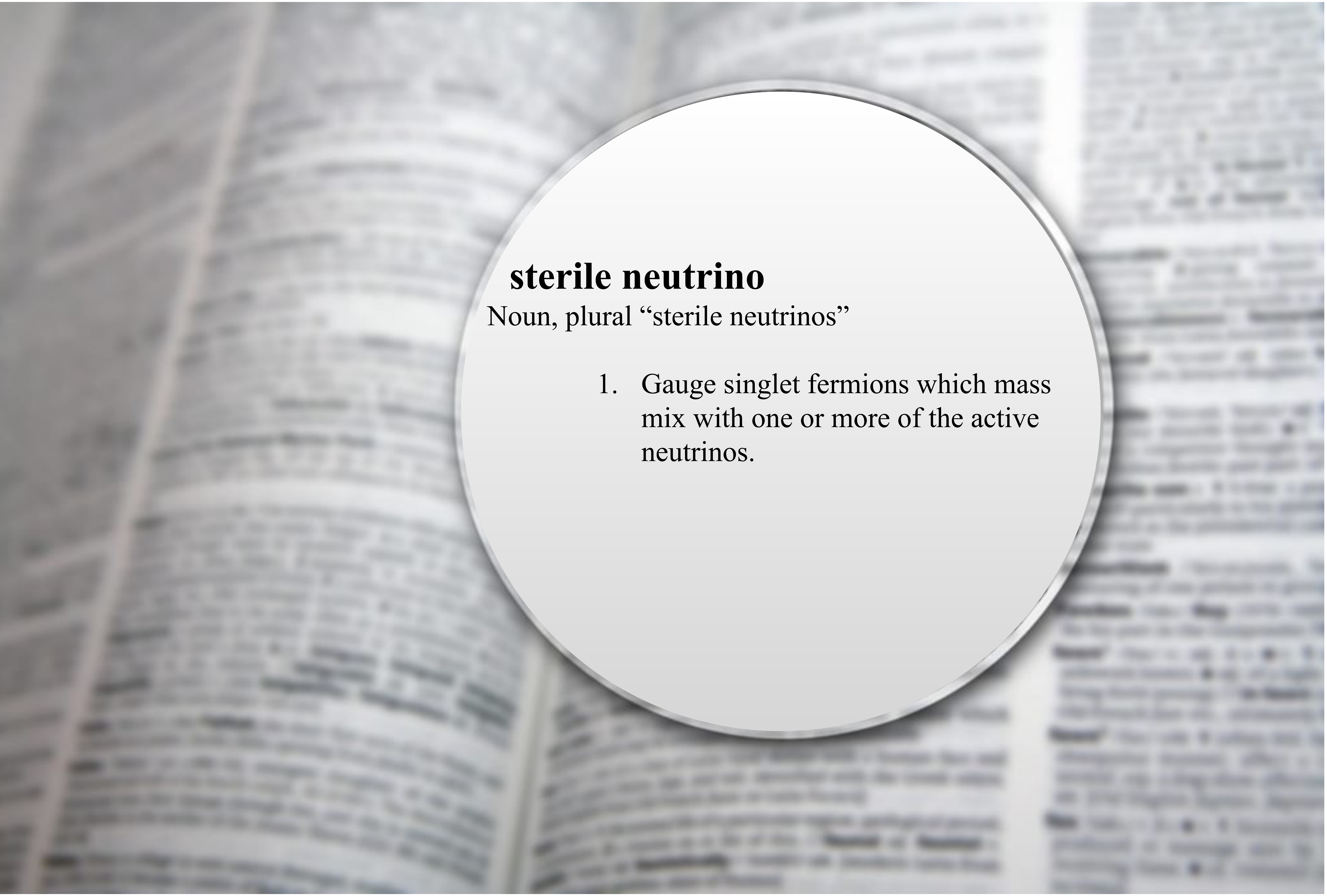
Theoretical Landscape for Sterile Neutrinos

Ian M. Shoemaker

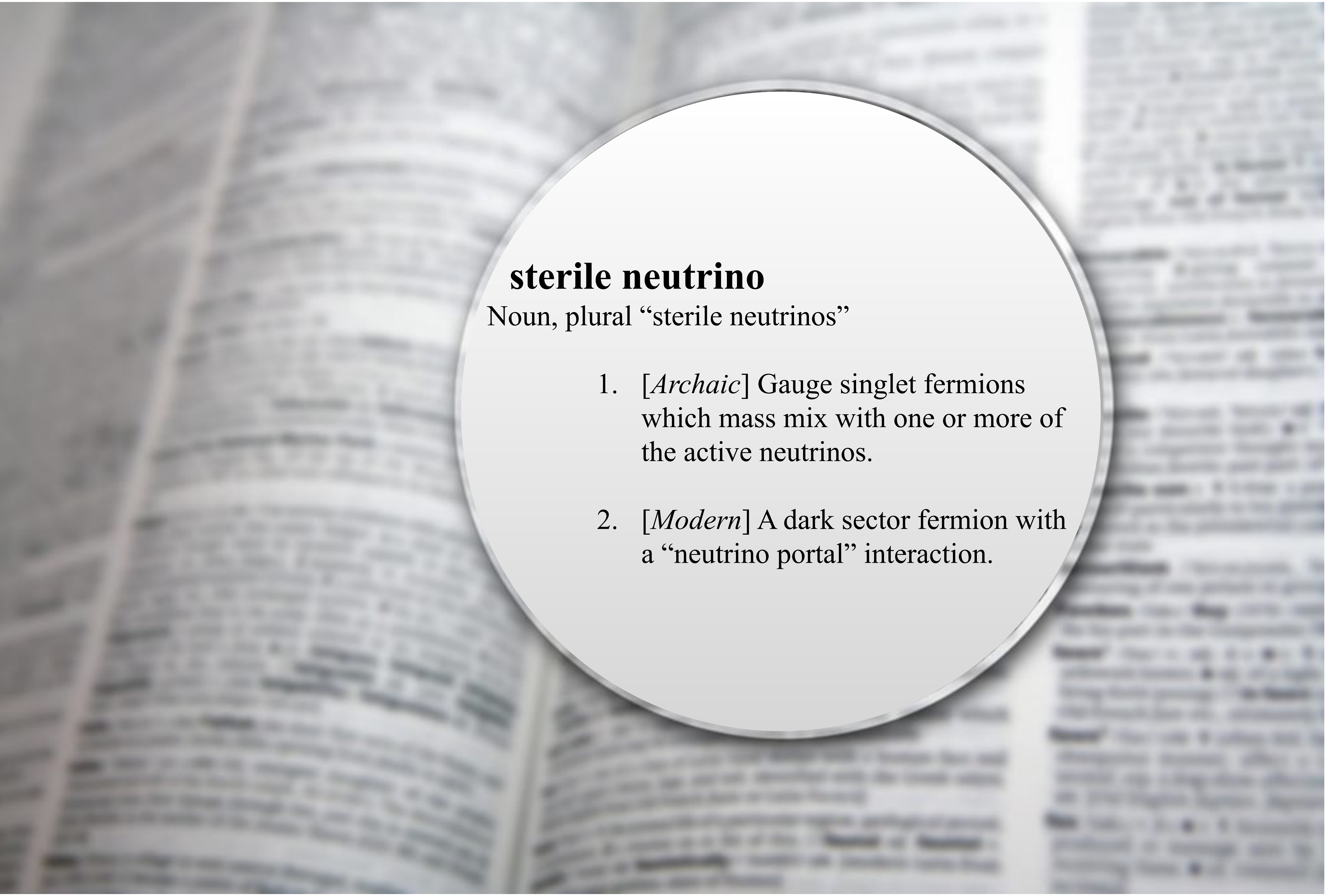
VIRGINIA TECH

Topics in Cosmic Neutrino Physics

October 10th, 2019



sterile neutrino
Noun, plural “sterile neutrinos”
1. Gauge singlet fermions which mass mix with one or more of the active neutrinos.


sterile neutrino
Noun, plural “sterile neutrinos”
1. [Archaic] Gauge singlet fermions which mass mix with one or more of the active neutrinos.
2. [Modern] A dark sector fermion with a “neutrino portal” interaction.

History

SOVIET PHYSICS JETP VOLUME 26, NUMBER 5 MAY, 1968

NEUTRINO EXPERIMENTS AND THE PROBLEM OF CONSERVATION OF LEPTONIC CHARGE

B. PONTECORVO

Joint Institute for Nuclear Research

Submitted June 9, 1967

Zh. Eksp. Teor. Fiz. 53, 1717–1725 (November, 1967)

The possible violations of leptonic charge conservation, which are compatible with experimental data, are large. This paper analyses various experimental setups which would be capable of detecting such hypothetical violations. It is shown that the most sensitive experiments are the search for the process $\mu \to e + \gamma$ and especially a search for oscillations of the type $\nu \rightleftarrows \overline{\nu}$ and $\nu_e \rightleftarrows \nu_\mu$. A nonvanishing neutrino mass could be related to CP-nonconservation and to an electric (and magnetic) dipole moment of the neutrino. Astronomical implications of the oscillation $\nu \rightleftarrows \overline{\nu}$ are discussed.

Neutrino oscillations can:

... convert potentially active particles into particle that are, from the point of view of the ordinary weak interactions, sterile, i.e. practically unobservable, since they have the "incorrect" helicity.

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Outline

- **Part 1: Truly sterile neutrinos:**
  - **Terrestrial tests**: Oscillations, production/decay.
  - **Extra-terrestrial tests**: Sterile Nu as a DM candidate.
- **Part 2: New but not sterile neutrinos:**
  - **Terrestrial:** IceCube, direct detection, SHiP,…
  - **DM connections** and the "neutrino portal."

Sterile Neutrinos

$$\{\nu_e, \nu_\mu, \nu_\tau, \boldsymbol{\nu}_{\boldsymbol{s},1}, \boldsymbol{\nu}_{\boldsymbol{s},2}, \ldots, \boldsymbol{\nu}_{\boldsymbol{s},N}\}$$

SM gauge singlets

Sterile Neutrinos

$$\{\nu_e, \nu_\mu, \nu_\tau, \boldsymbol{\nu_{s,1}}, \boldsymbol{\nu_{s,2}}, \ldots, \boldsymbol{\nu_{s,N}}\}$$

SM gauge singlets

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\nu}_{s,a}\left(i\partial_\mu \gamma^\mu\right)\nu_{s,a} - y_{\alpha a} H\, \bar{L}_\alpha \nu_{s,a} - \frac{M_{ab}}{2}\,\bar{\nu}^c_{s,a}\nu_{s,b} + h.c.\,,$$

Mass Matrix: $$M = \begin{pmatrix} 0 & D_{3\times N} \\ D^T_{N\times 3} & M_{N\times N} \end{pmatrix}$$

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- **Unlike SM fermions, their # is not constrained by anomaly cancellation.**
- **Don't know the number of steriles!**
- **Need at least two of them for atm/sol mass splittings N =2.**
- **If N=3, can accommodate oscillations and DM if one is at the keV scale.**

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How can we find them?

1) Modified oscillations

2) Up-scattering production

3) Meson decay production

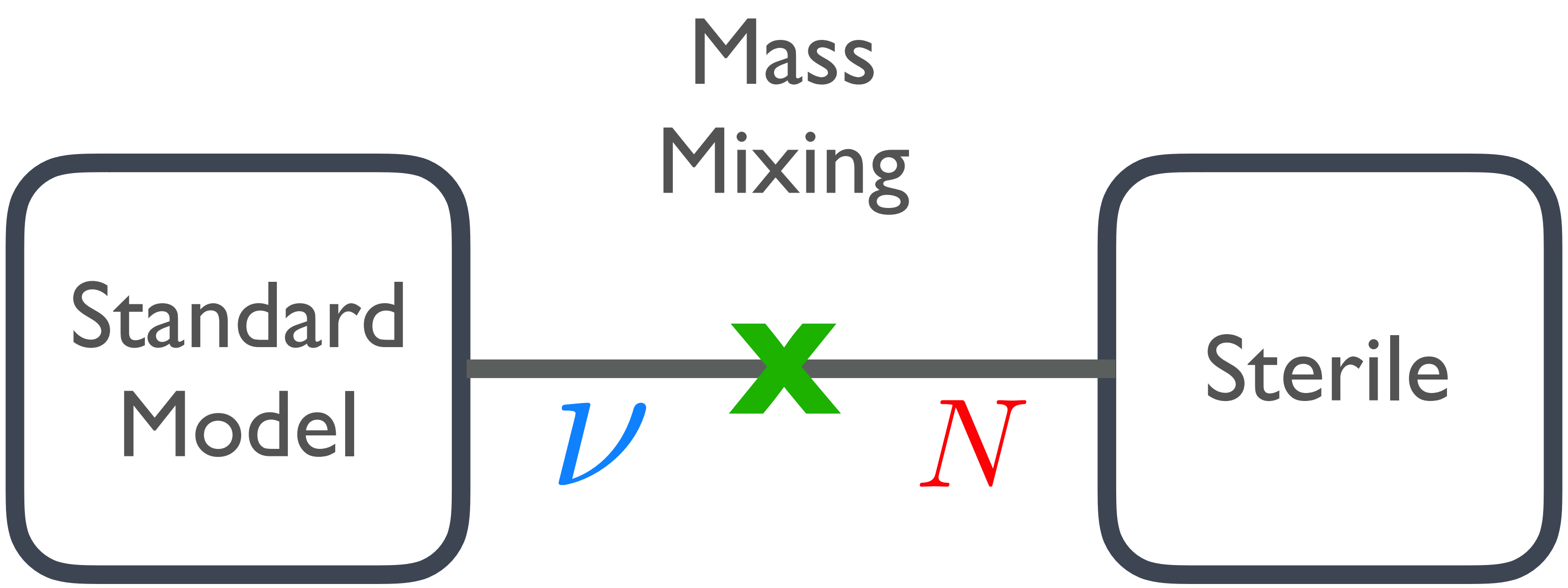
...

Part 1

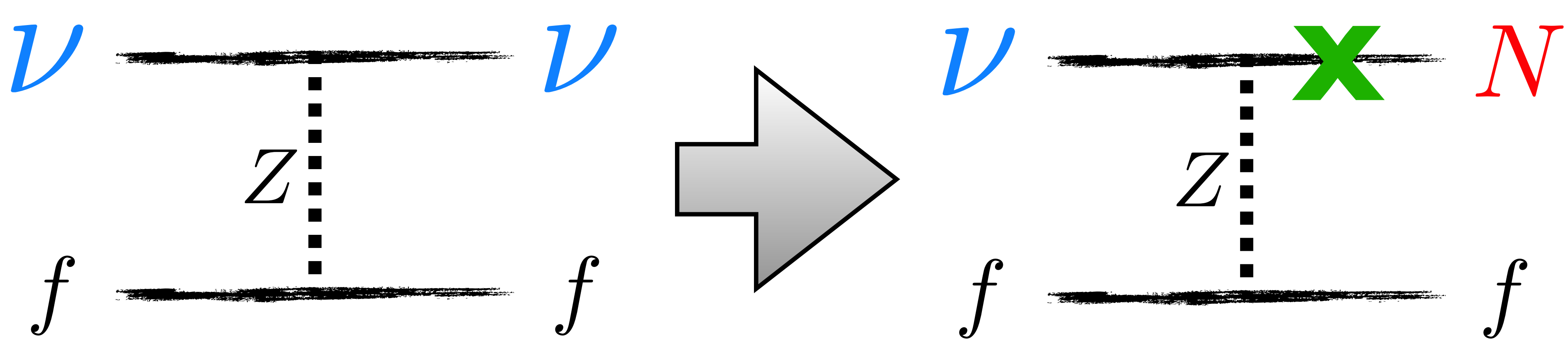
Truly Sterile Neutrinos

-Dark Matter
-Detecting non-DM sterile:
up-scattering production @Icecube

Inheriting Weak Interaction



For example:



$$\sigma_{\nu\to N} \sim \theta^2 \sigma_{\rm SM}$$

DM from Neutrino Scattering

Dodelson, Widrow (1993)

Oscillations + Collisions in expanding Universe:

$$\left(\frac{\partial}{\partial t} \; - \; HE\frac{\partial}{\partial E}\right) f_S(E,t) \; = \; \left[\frac{1}{2}\sin^2(2\theta_M(E,t)) \; \Gamma(E,t)\right] f_A(E,t)$$

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Mechanism gives correct DM abundance if:

$$\boxed{\rightarrow\ \sin^2(2\theta) \simeq 9\times 10^{-10}\left(\frac{g_*(T=100\ \mathrm{MeV})}{20}\right)^{1/2}\left(\frac{10\ \mathrm{keV}}{m_s}\right)^2}$$

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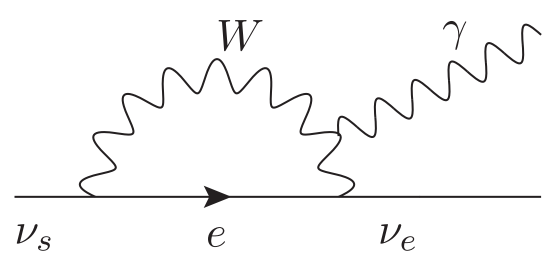
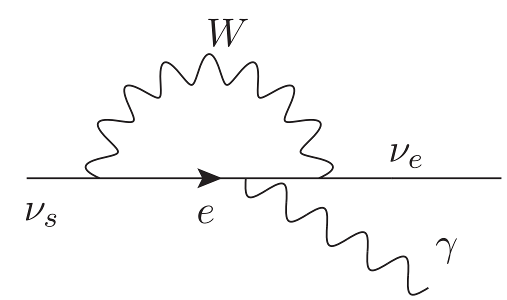
Peak production occurs when "collision rate" = "oscillation rate":

$$T_{\mathrm{max}} \simeq (m_s/G_F)^{1/3} \simeq 200\ \mathrm{MeV}\ \left(\frac{m_s}{\mathrm{keV}}\right)^{1/3}$$

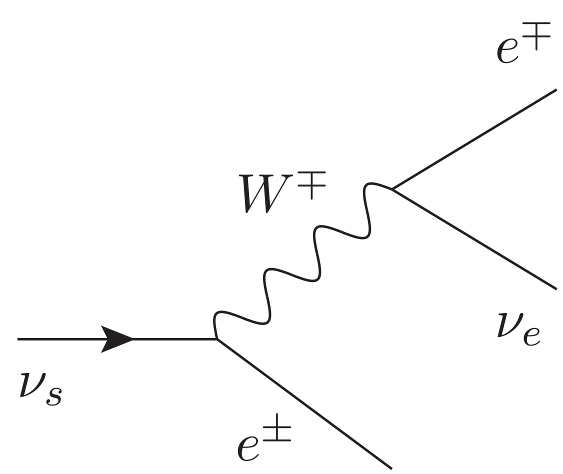
How do you detect it?

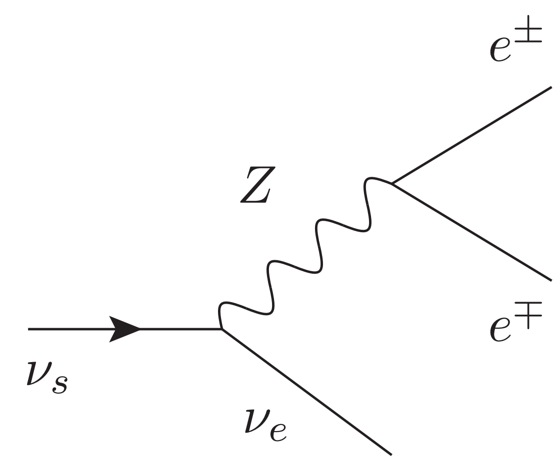
Sterile Neutrino DM is unstable





X-ray lines!





gamma spectrum

Sanity check: Stable on universe lifetime scales.

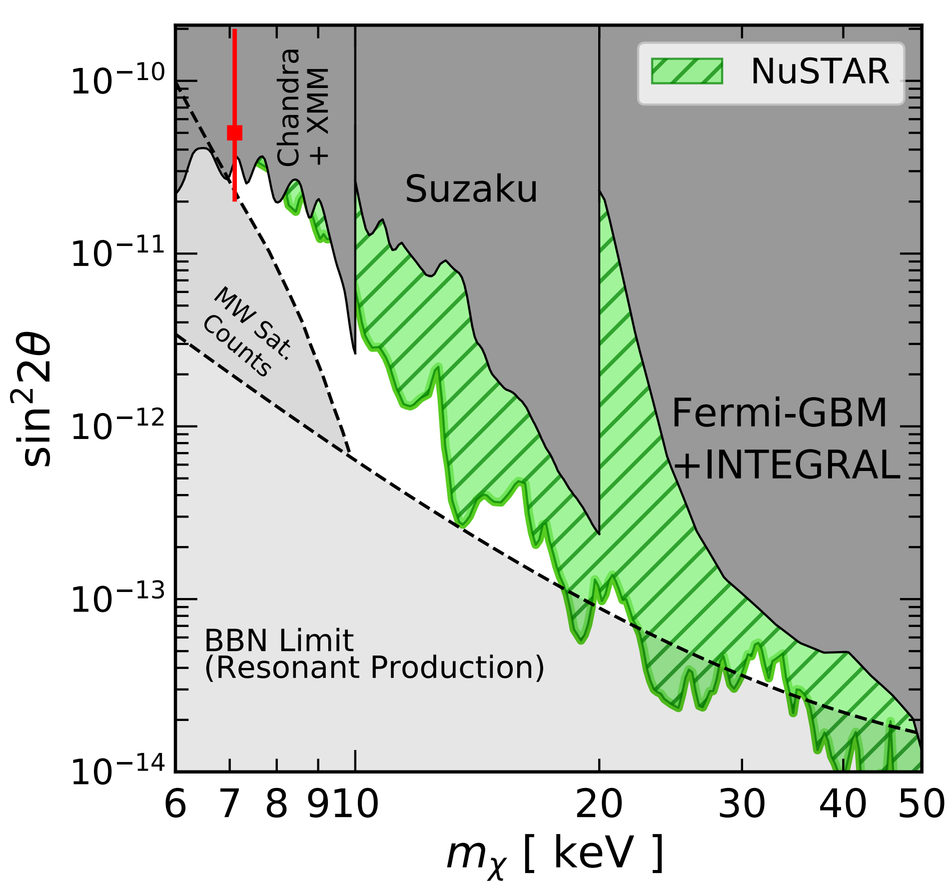
$$\Gamma \sim \sin^2 2\theta G_F^2 m_s^5 \qquad \Rightarrow \sin^2 2\theta \lesssim 0.06 \left(\frac{10\ \mathrm{keV}}{m_s}\right)^5$$

Dodelson-Widrow doesn't work for DM above ~700 keV masses.

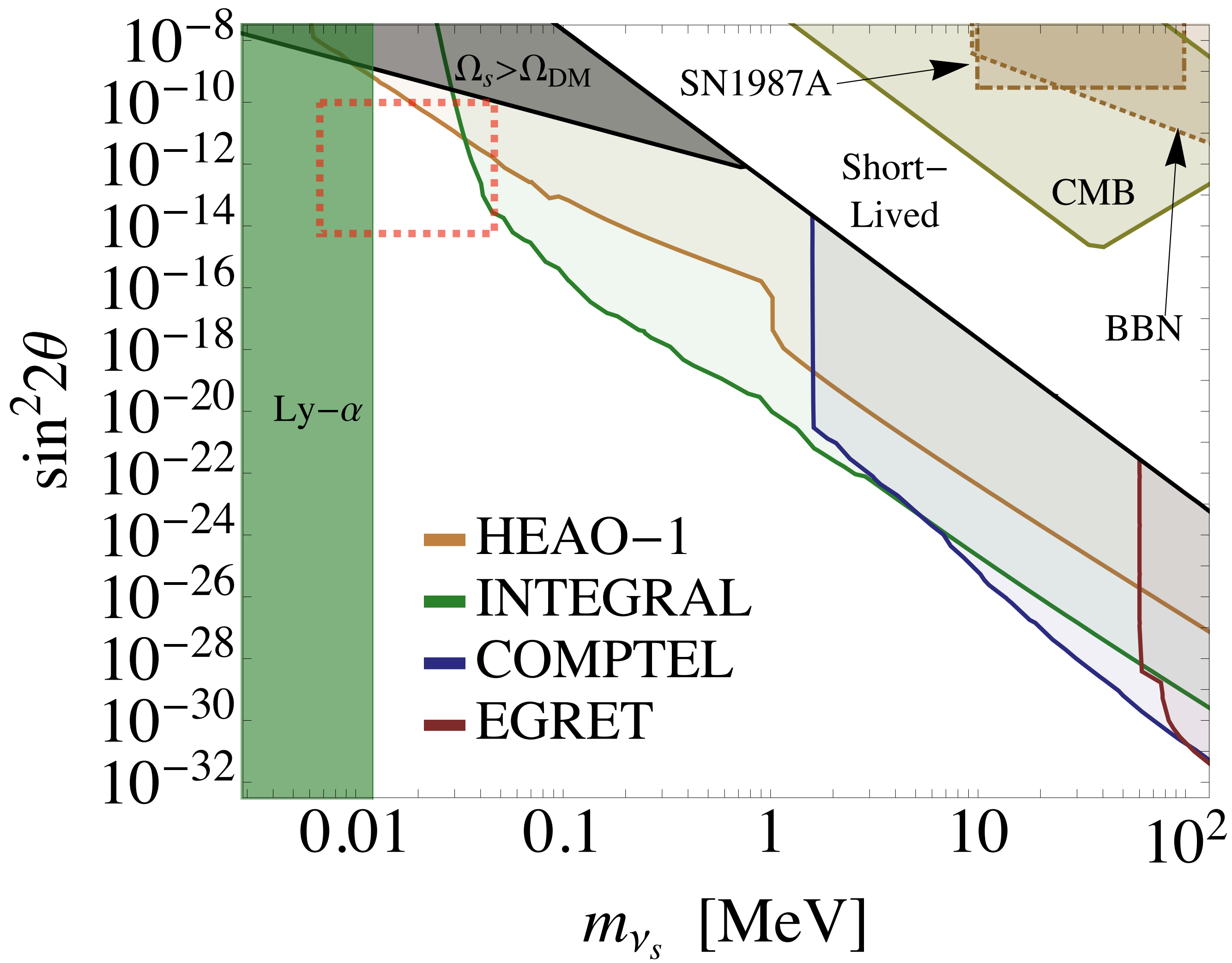
X-ray limits are strong

$$\rightarrow \sin^2(2\theta) \simeq 9 \times 10^{-10} \left(\frac{g_*(T=100\ \mathrm{MeV})}{20}\right)^{1/2} \left(\frac{10\ \mathrm{keV}}{m_s}\right)^2$$

Roach et al, [1908.09037]



Essig et al, [1309.4091]



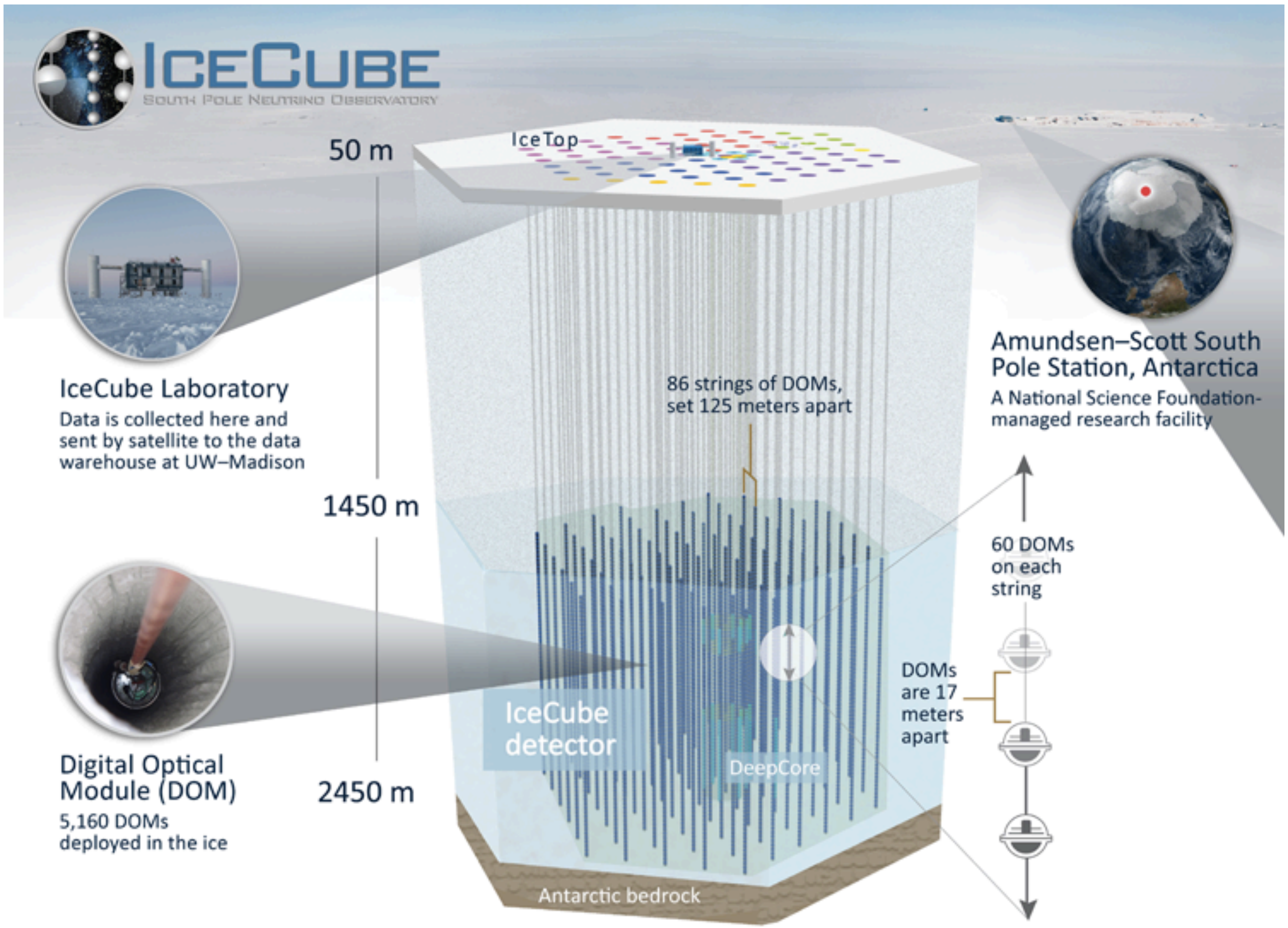
Strongly **excludes minimal DM production mode.**

Variations

- Change production:
    - Lepton asymmetry [Shi, Fuller (1998)]
    - Singlet Higgs Decay [Kusenko (2006); Kusenko, Petraki (2007)]
    - Time-dependent VEVs [Bezrukov, Chudaykin, Gorubnov (2018)].
    - Gauged B-L [Shuve, Yavin (2014)].
    - Neutrino self-interactions [See Johns and Sen talks].

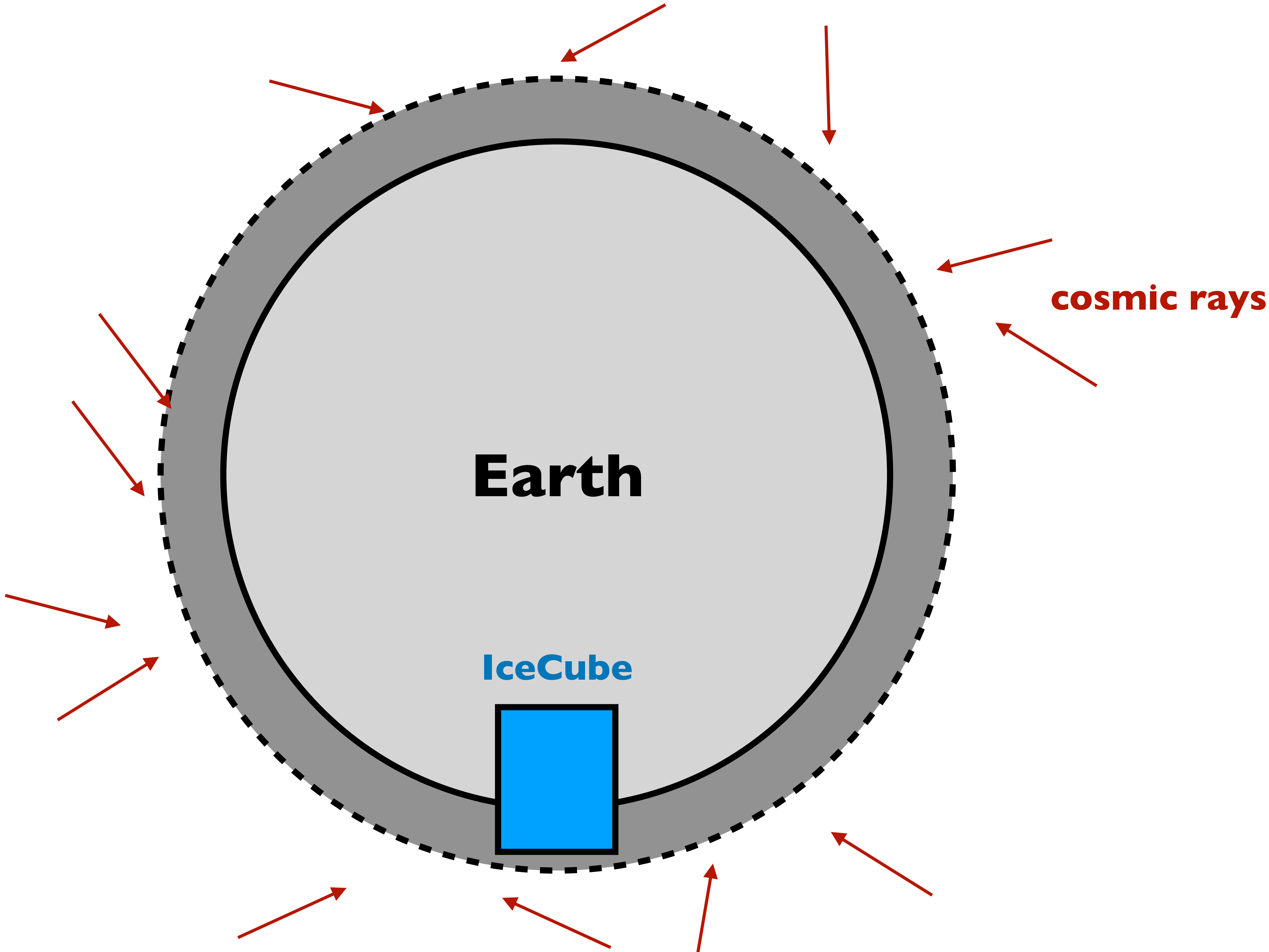
Too heavy to be DM?

New Physics Signatures at IceCube



Atmospheric Neutrinos as a BSM probe

Coloma, Machado, Martinez-Soler, Shoemaker 2017, Phys. Rev. Lett. **119**, 201804



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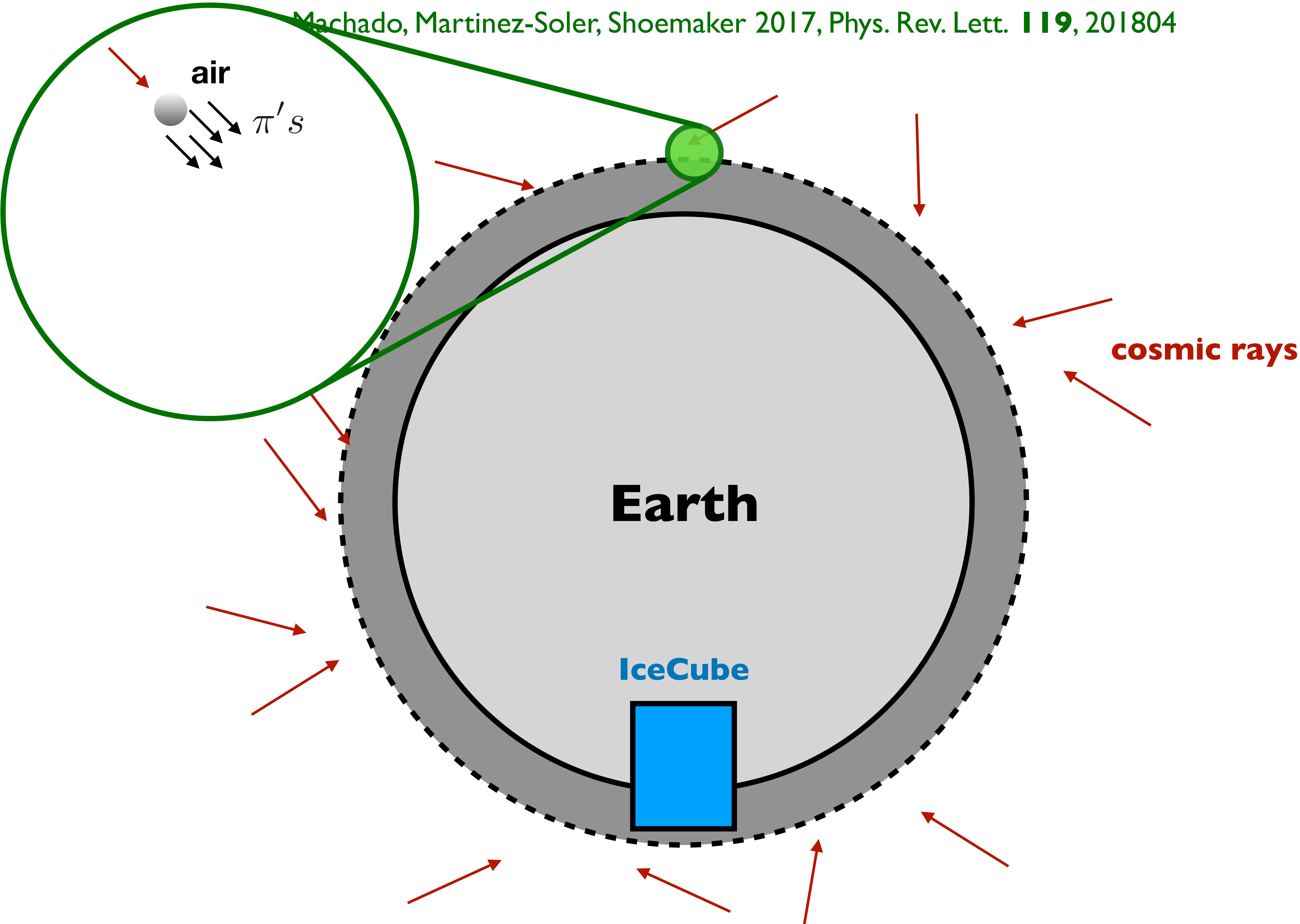

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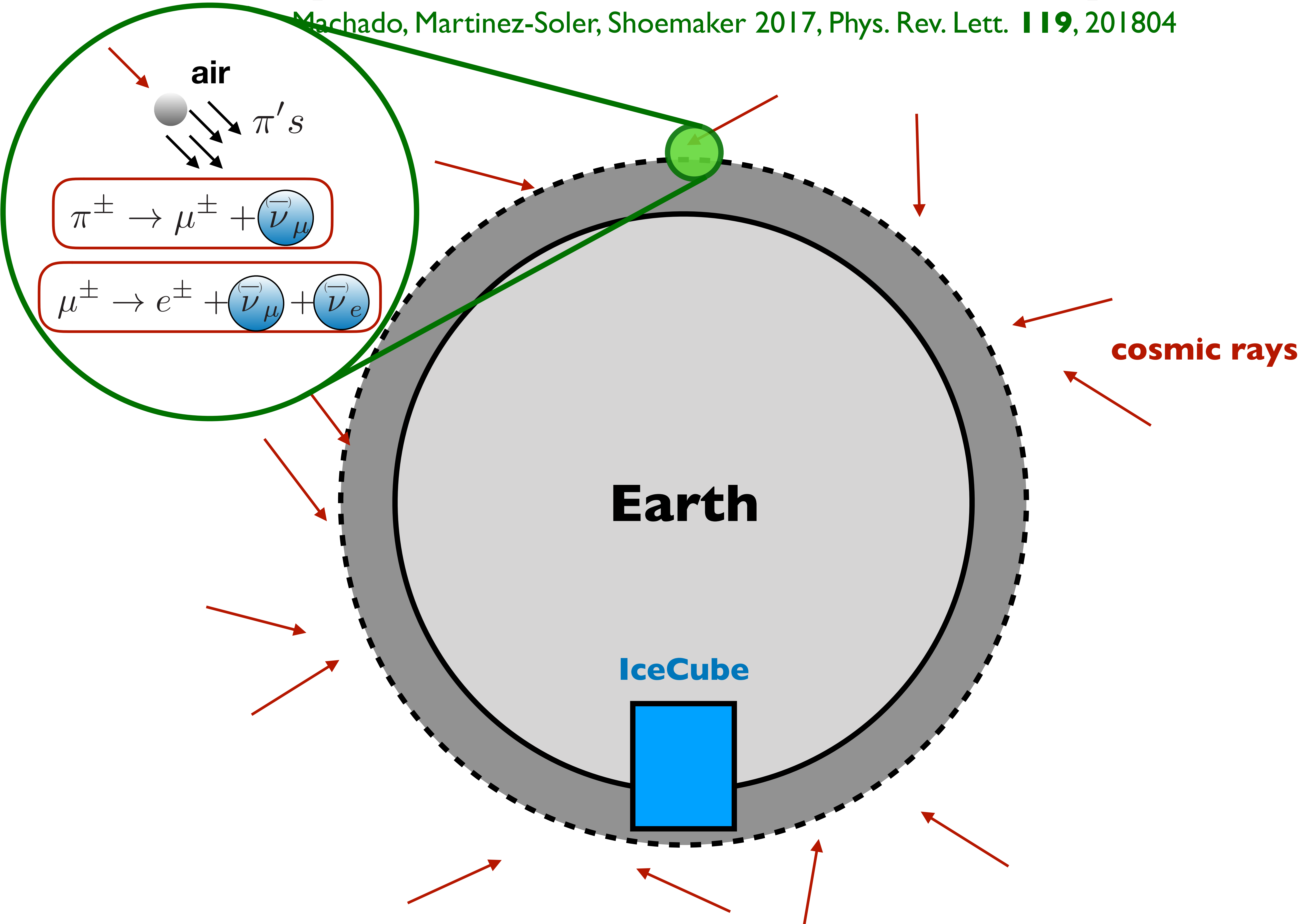

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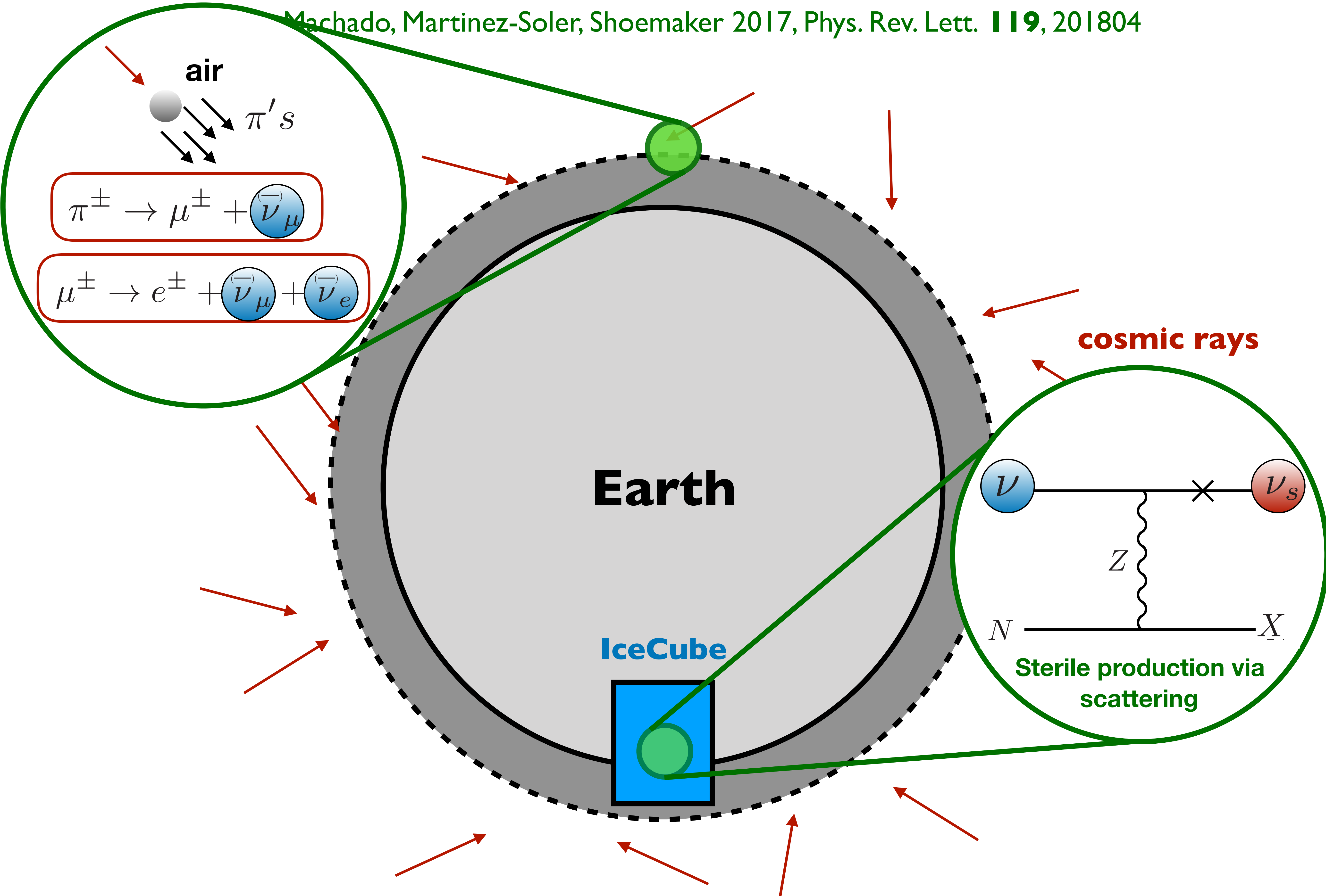
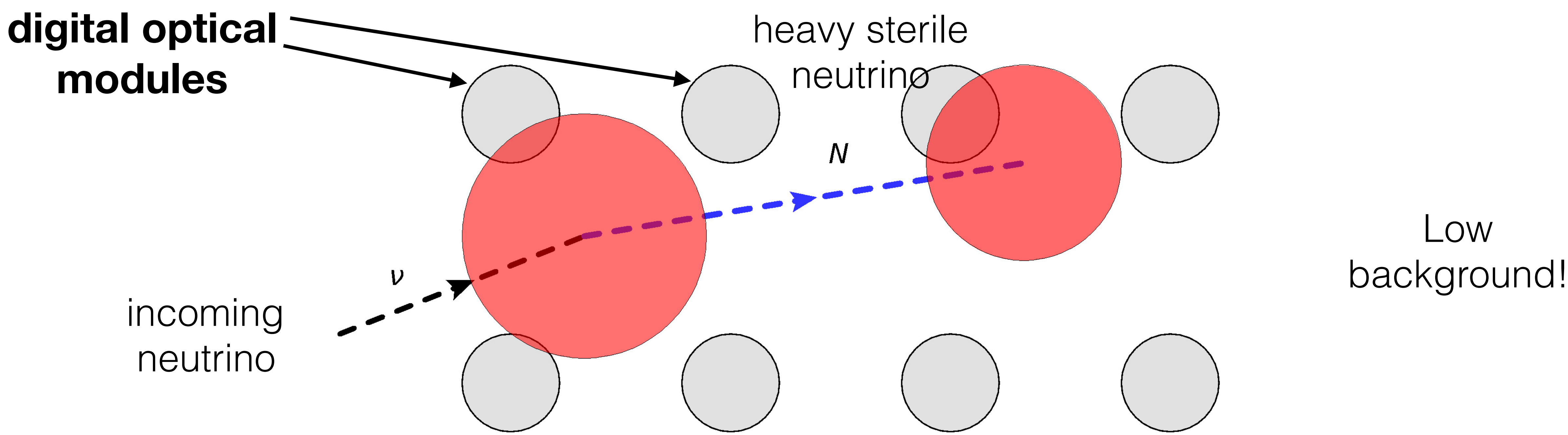
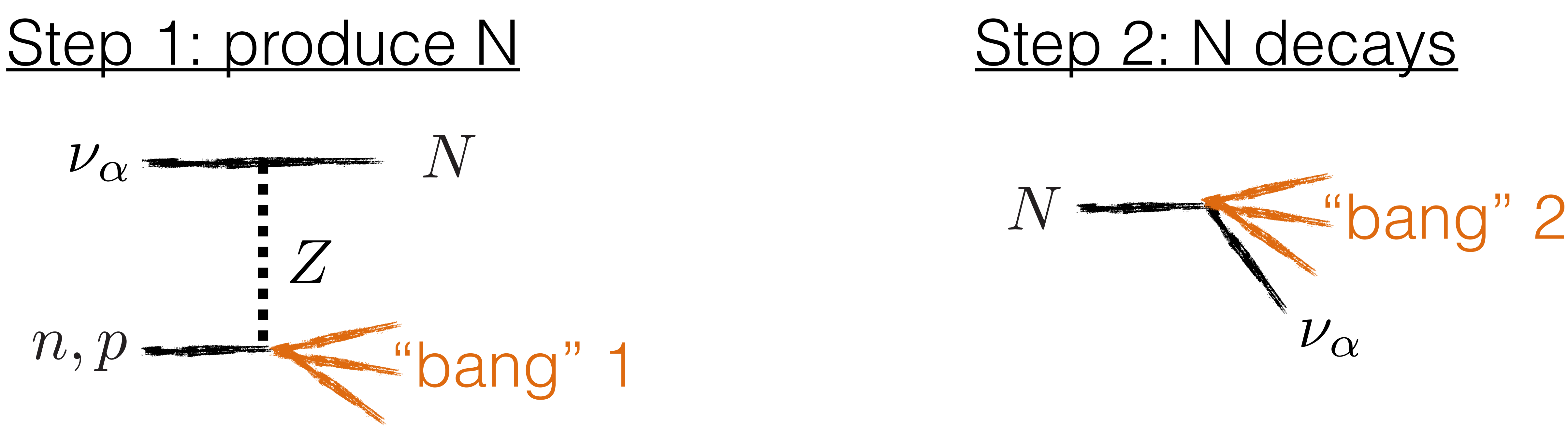


“Double-bangs” from Sterile Neutrinos

Coloma, Machado, Martinez-Soler, Shoemaker 2017, Phys. Rev. Lett. **119**, 201804





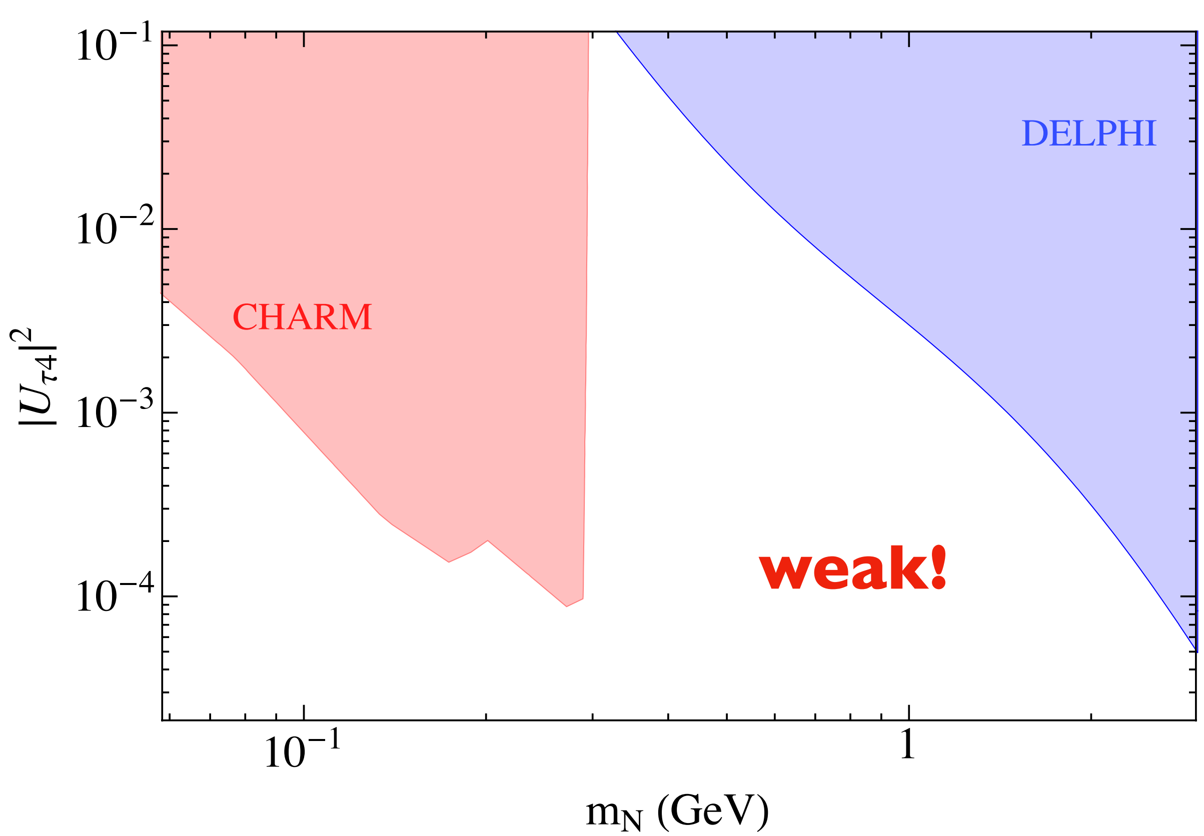
No extra radiation between steps 1 and 2.

Existing Constraints

- **Assume sizable mixing with only one heavy neutrino**

$$\nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i}\nu_{iL} + U_{\alpha 4} N_{4R}^{c}$$

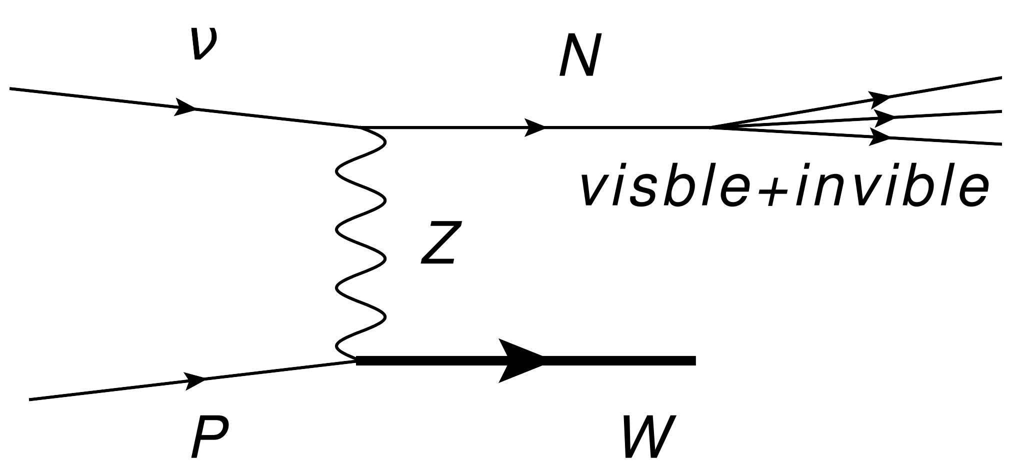
tau-flavor



A. Atre, T. Han, S. Pascoli, and B. Zhang, JHEP 05, 030 (2009), arXiv:0901.3589 [hep-ph] .

Boosted decay length

$$N_4 \rightarrow \text{visible} + \text{invisible}$$



$N_4 \rightarrow \nu_l P^0$ (Pseudoscalar mesons)
$N_4 \rightarrow \nu_l V^0$ (Neutral vector mesons)
$N_4 \rightarrow l^- P^+$ (Charged pseudoscalar mesons)
$N_4 \rightarrow l^- V^+$ (Charged vector mesons)
$N_4 \rightarrow \tau \nu_l l^+ \ \tau$
$N_4 \rightarrow \nu_{l_1} l_2^+ l_2^-$
$N_4 \rightarrow \nu \nu \bar{\nu}$

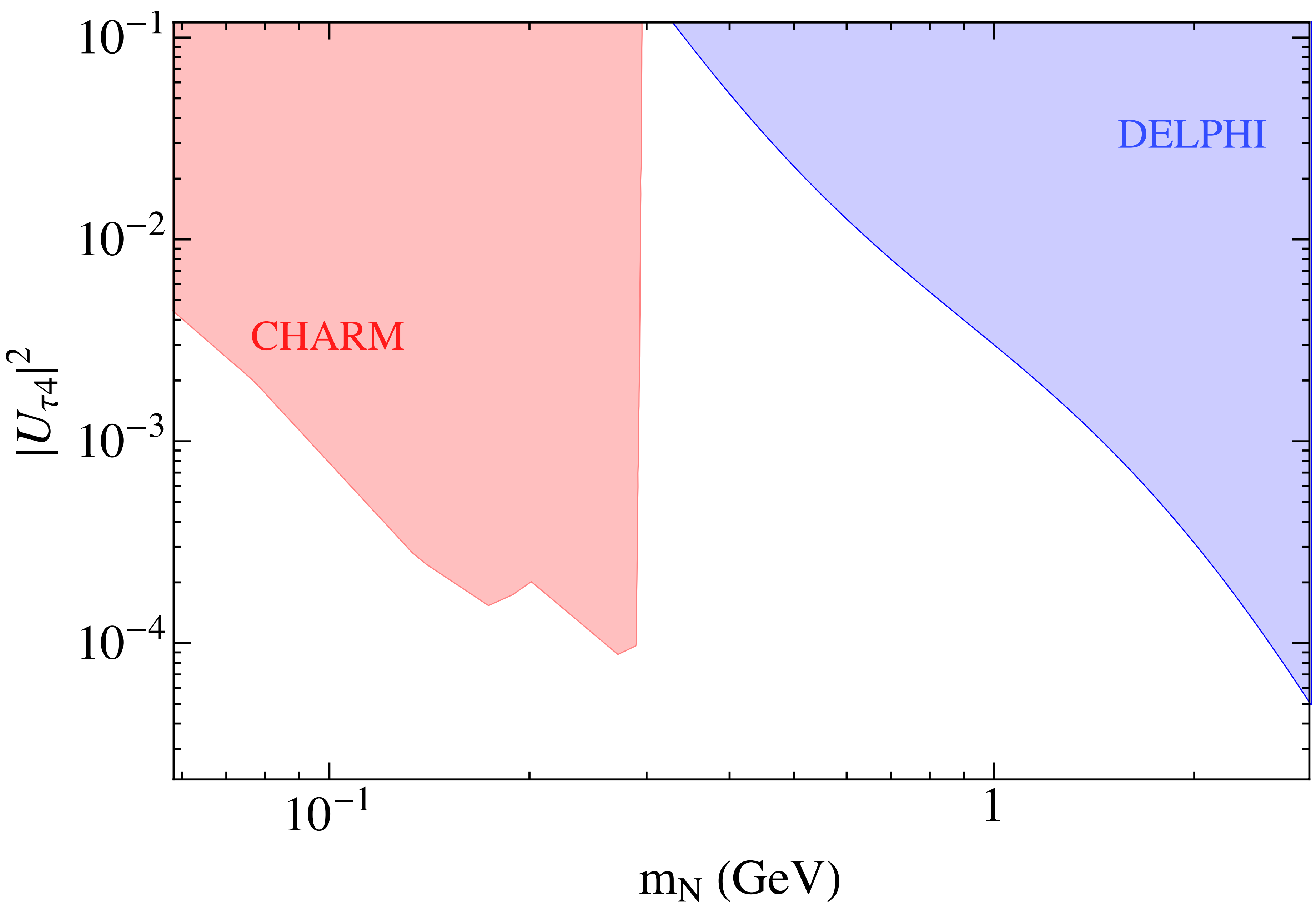
Example

$m_N = 1$ **GeV and** $|U_{\tau 4}|^2 = 10^{-3}$

and 10 GeV boost $\Rightarrow \mathrm{L_{lab}} \sim 20$ m

Coloma, Machado, Martinez-Soler, Shoemaker 2017, Phys. Rev. Lett. **119**, 201804

Heavy Neutrinos from the Atmosphere



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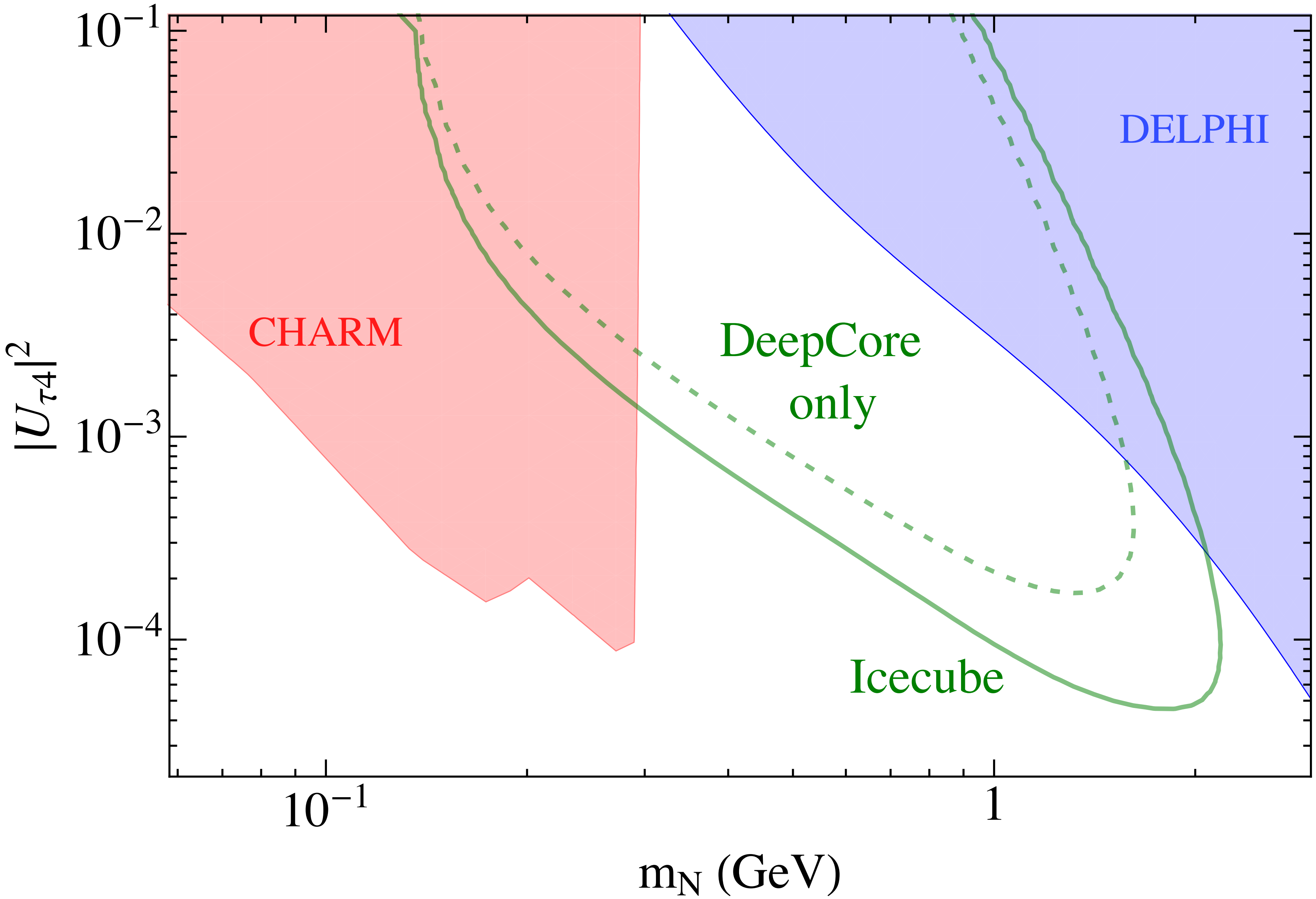

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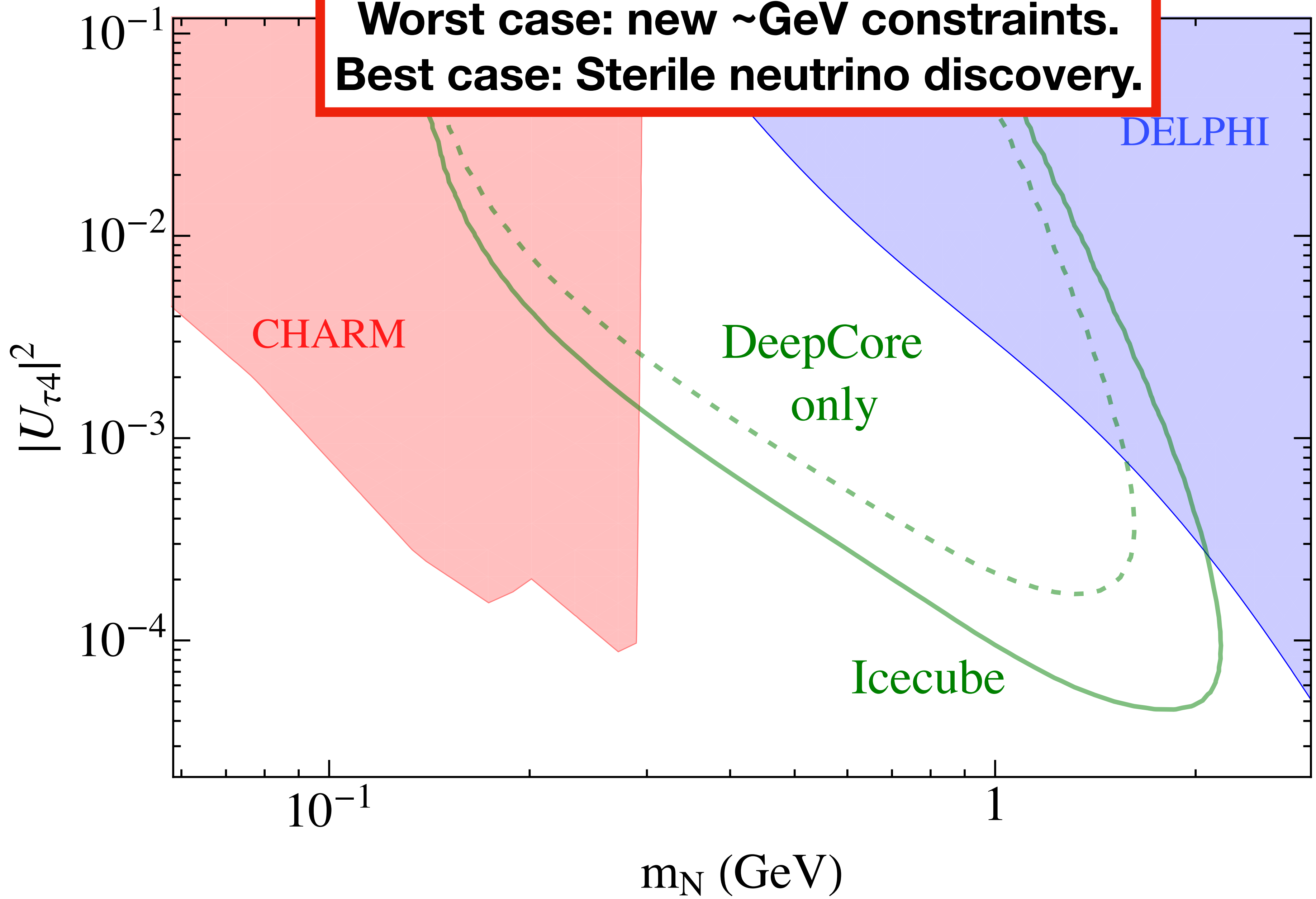
Heavy Neutrinos from the Atmosphere

Assumes only existing data.
Worst case: new ~GeV constraints.
Best case: Sterile neutrino discovery.



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Part 2

New but not Sterile :
ν_s + new interactions

- -Higher-dim operators
- -New gauge interactions
- -Dark Matter Connections

Why?

- We like Occam. Nature doesn't always seem to.
- Dark Matter may suggest an entirely new sector of particles/ forces.
- New theory ideas often:
    - Incite new experimental strategies.
    - Interpret existing data in a new way.
    - Novel synergistic complementarity of experiments.

Neutrino Portal DM

- New fermion singlets are DM = sterile neutrino DM [Dodelson-Widrow (1993)].
- New fermion singlets are not DM, but act as messenger between SM and dark sector.
    - Small-scale structure modifications from late DM kinetic decoupling. [Dasgupta, Kopp (2015); Cherry, Friedland, IMS (2014); Ipek, McKeen, Nelson (2015); Batell, Han, McKeen, Haghi (2017)].
    - Neutrino scattering @ IceCube [Cherry, Friedland, IMS (2014,2016)].
    - Modified neutrino oscillations from ambient DM [Capozzi, IMS, Vecchi (2017); Brdar, Kopp, Liu, Prass, Wang (2017); Krnjaic, Machado, Necib (2017); Capozzi, IMS, Vecchi (2018)].
    - …

Potential EM Properties of Sterile Neutrinos

-Don't know dominant Sterile Neutrino -SM "portal"
-Could be higher-dim. operator.

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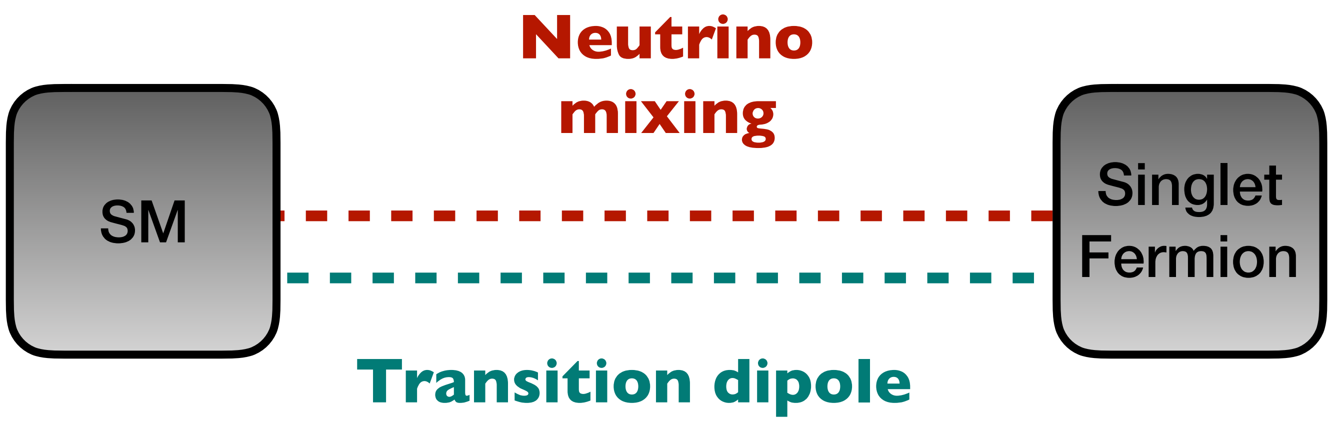
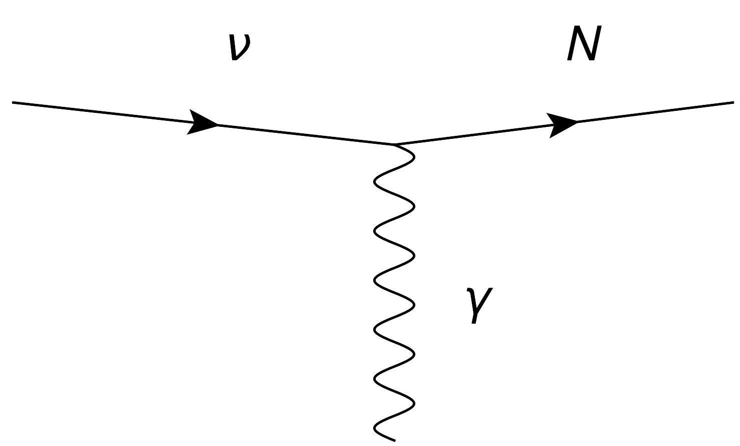
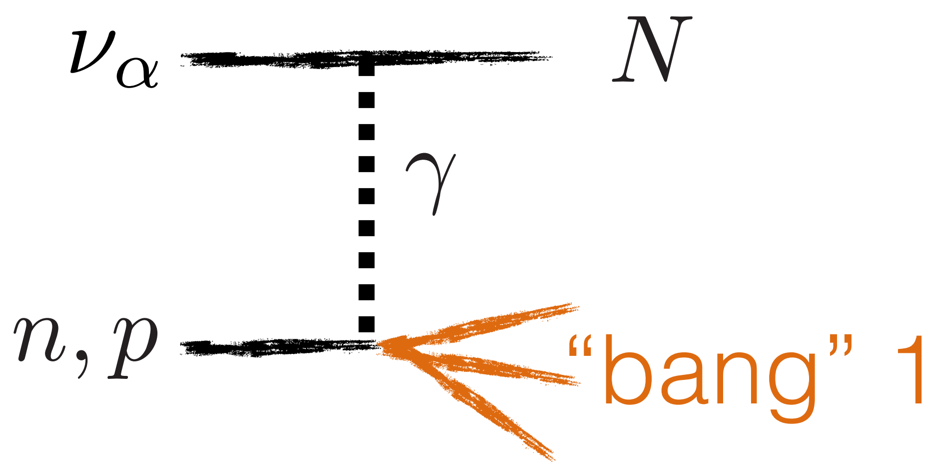


$$\mathcal{L} \supset -\mu_\nu \bar{N}_4 \sigma_{\mu\nu} P_L \nu_\alpha F^{\mu\nu}$$



Potential EM Properties of Sterile Neutrinos

Step 1: produce N



Step 2: N decays

Potential EM Properties of Sterile Neutrinos

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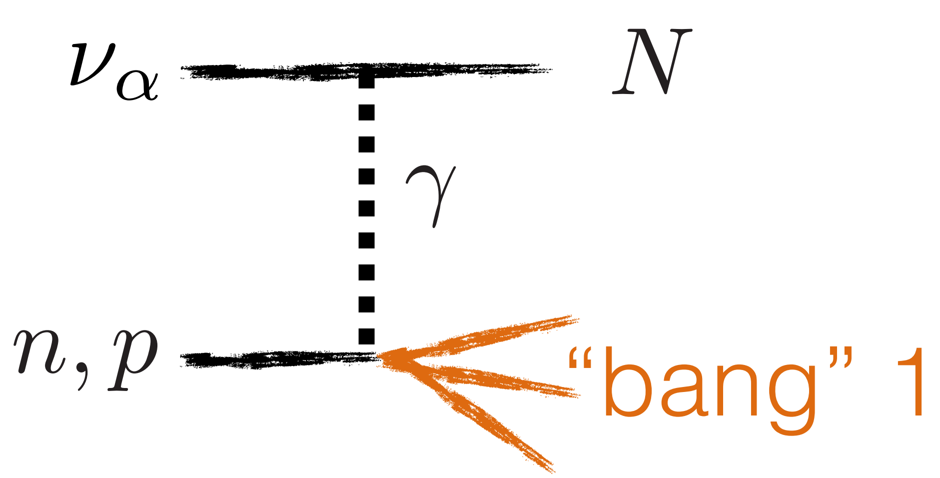

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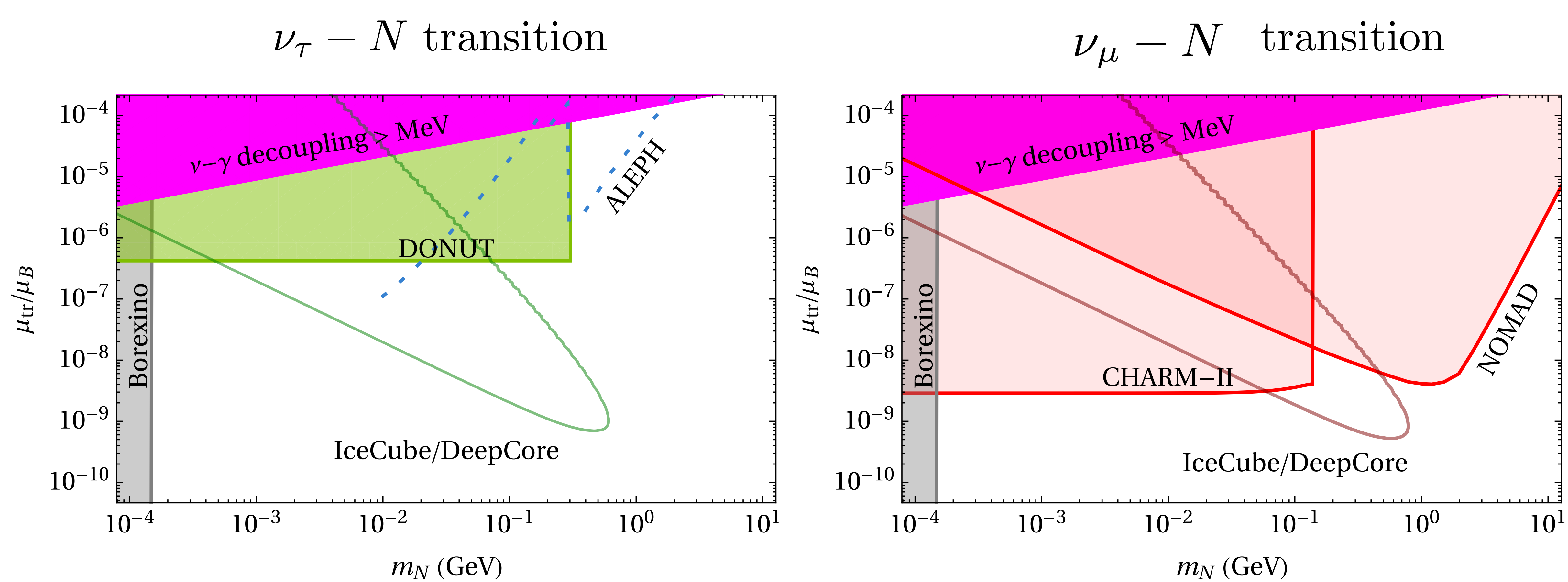


Coloma, Machado, Martinez-Soler, Shoemaker 2017, Phys. Rev. Lett. **119**, 201804

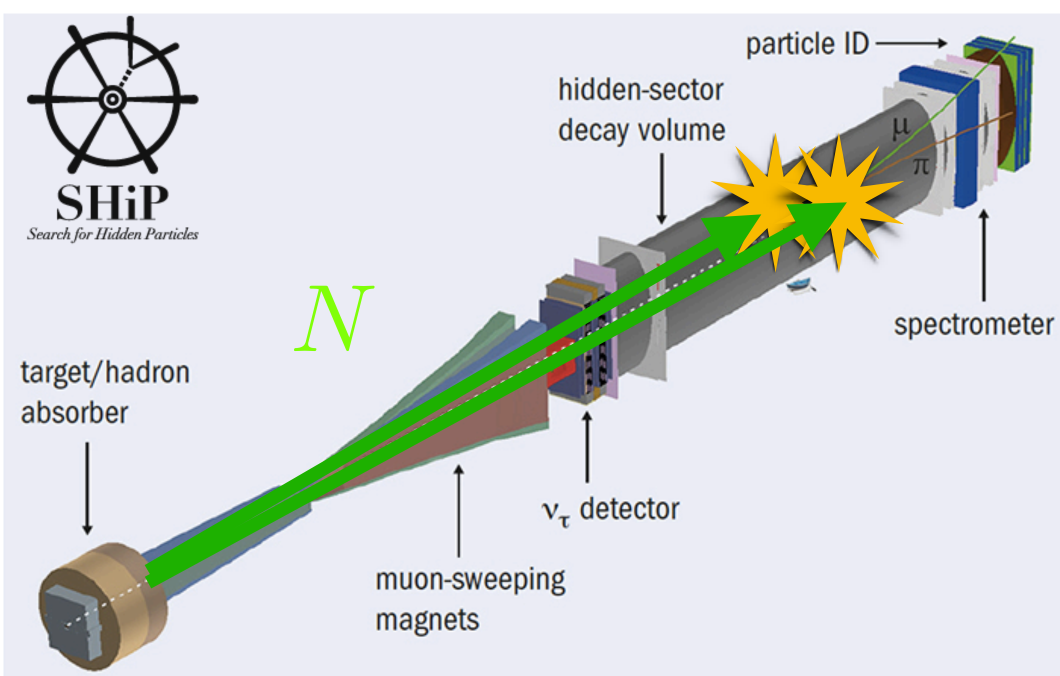
Dipole portal to heavy neutral leptons

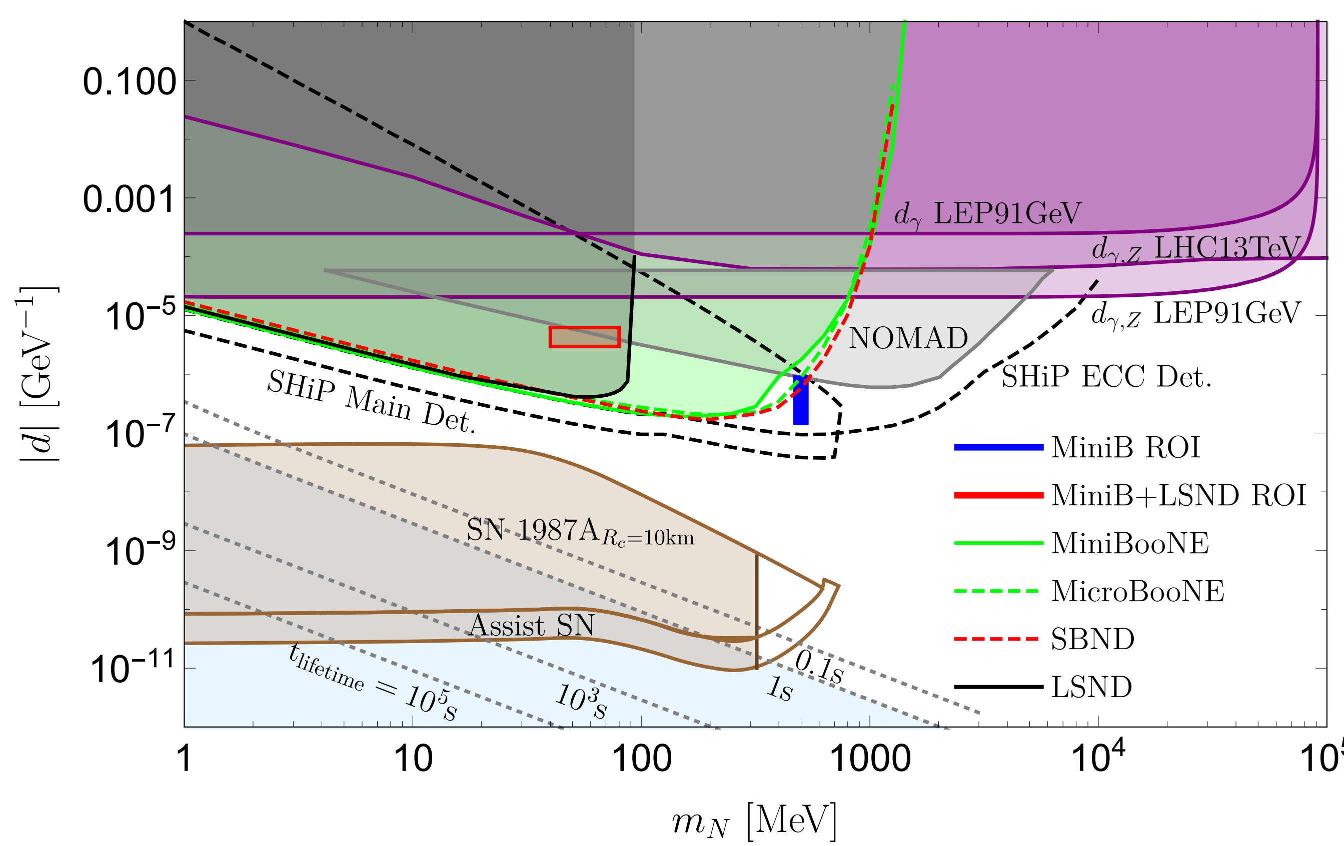
Magill, Plestid, Pospelov, Tsai [1803.03262]

$$\mathcal{L} \supset \bar{N}(i\partial\!\!\!/ - m_N)N + (d\bar{\nu}_L \sigma_{\mu\nu} F^{\mu\nu} N + h.c).$$

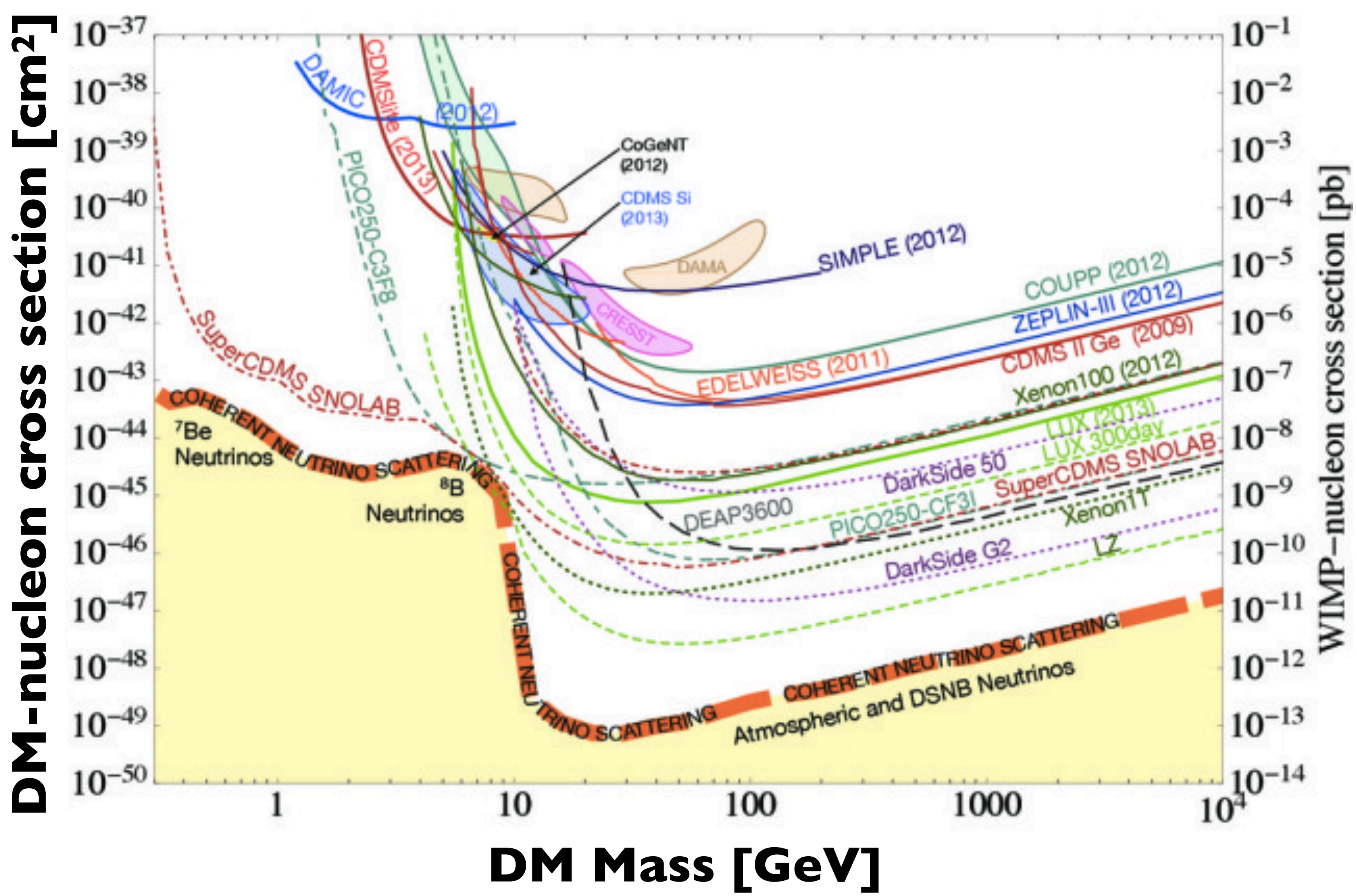
- **Systematically examine production mechanisms: up-scattering, off-shell photon, meson decays.**
- **Astrophysics-terrestrial experiment complementarity.**

high-intensity SHiP beam dump experiment





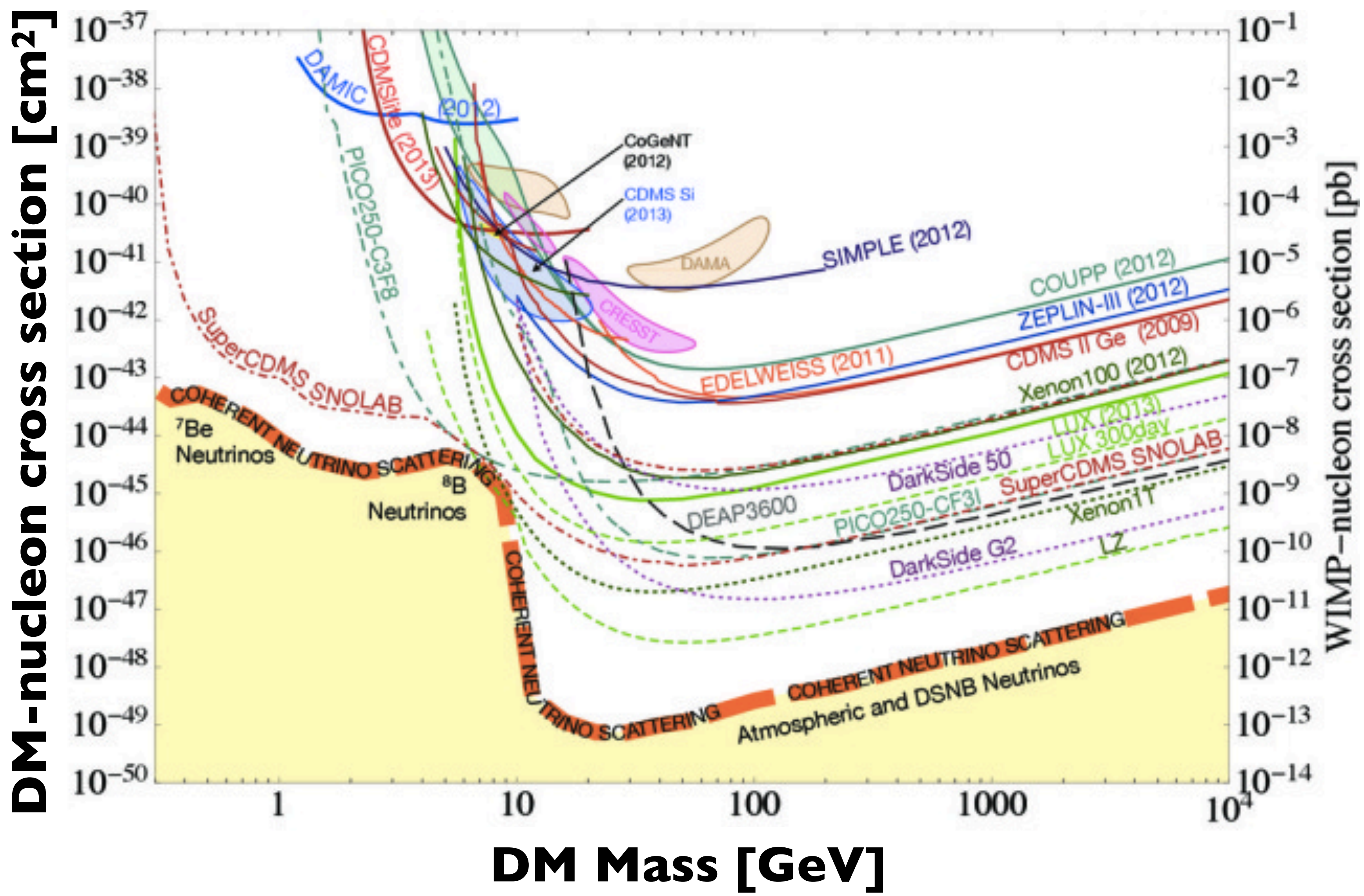
Future of DM Direct Detection



Eventually run into a "neutrino floor." Bad for DM, but good for neutrinos!

Future of DM Direct Detection

bigger experiments



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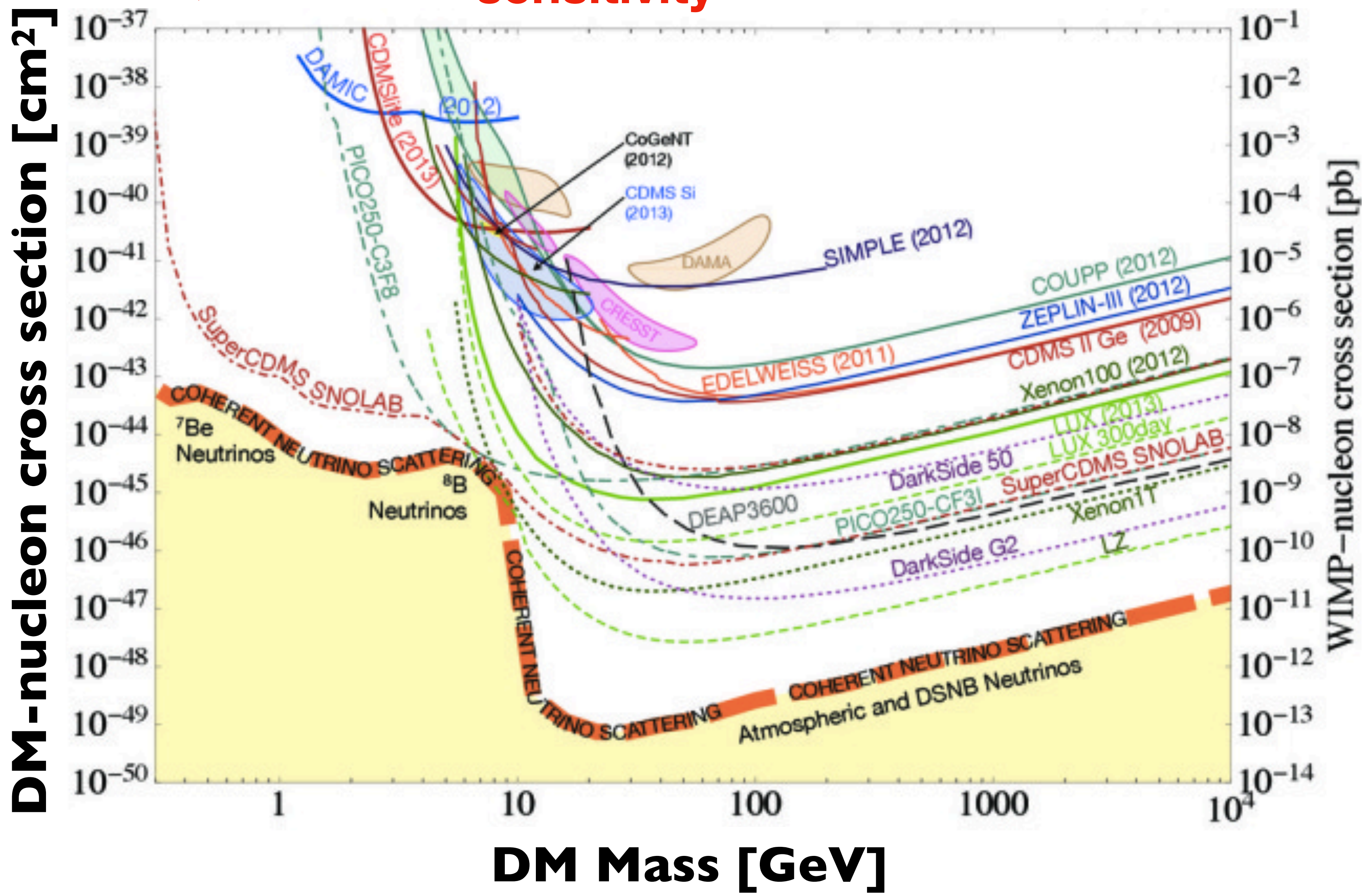
Future of DM Direct Detection

smaller energy sensitivity

bigger experiments



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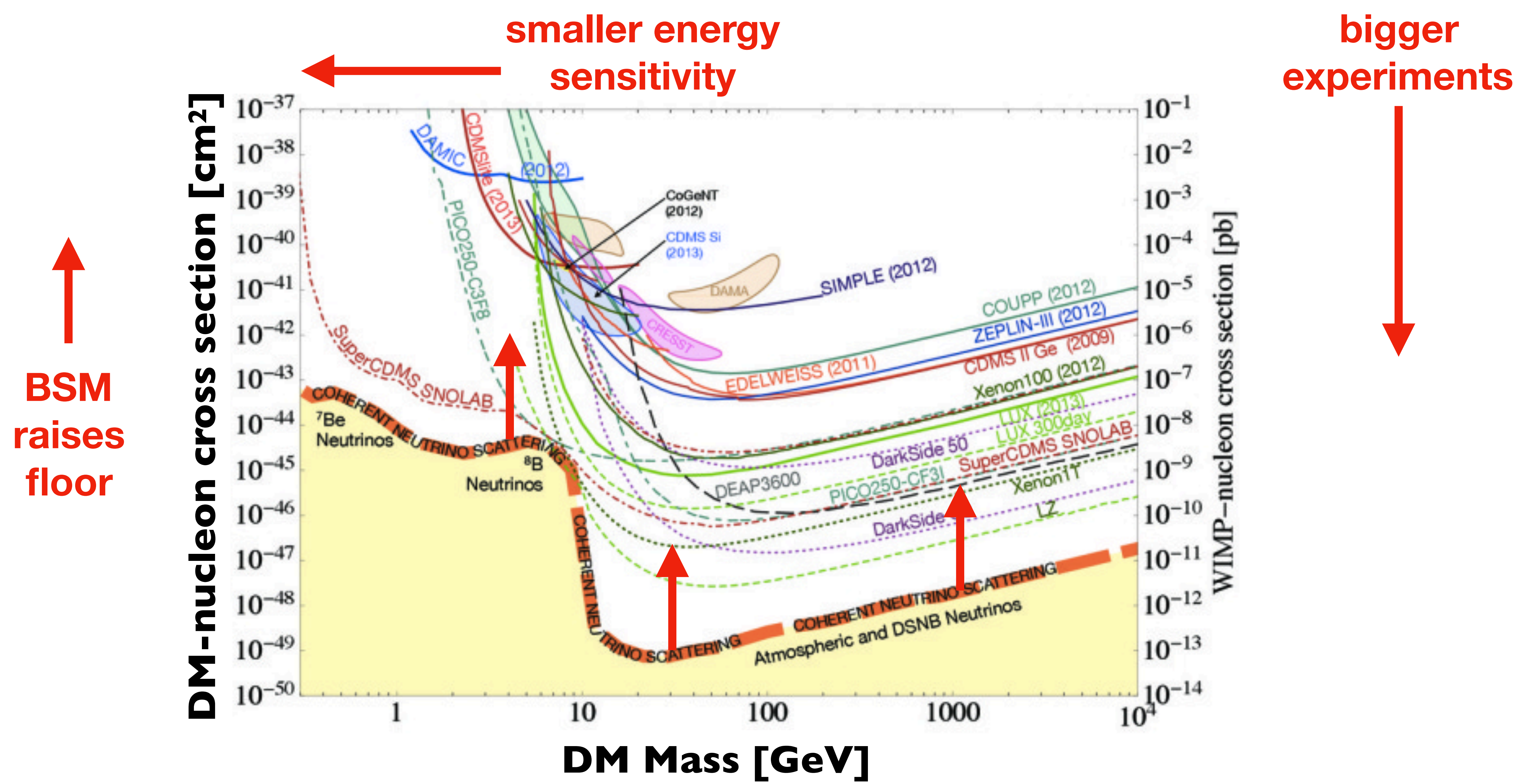

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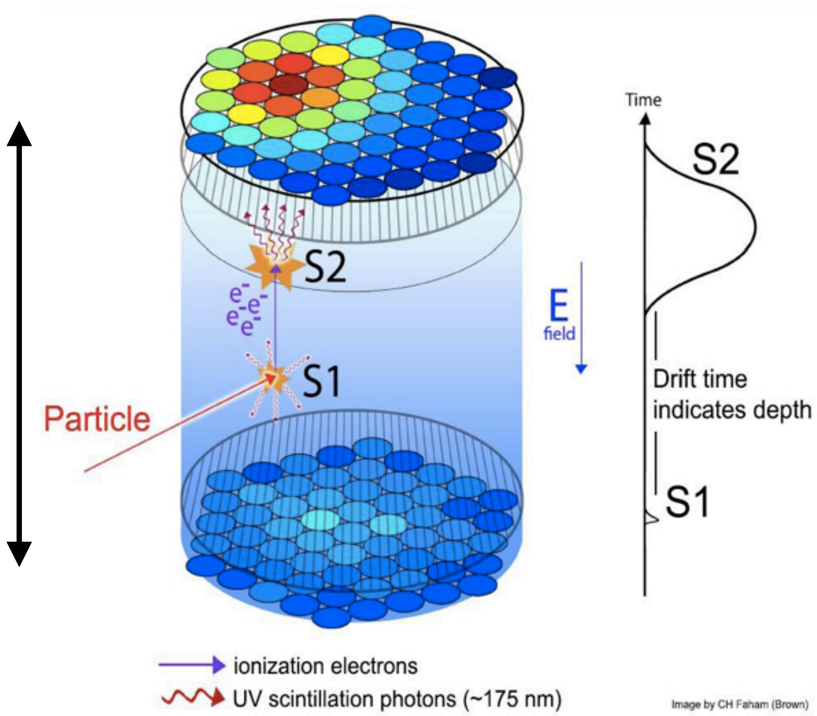
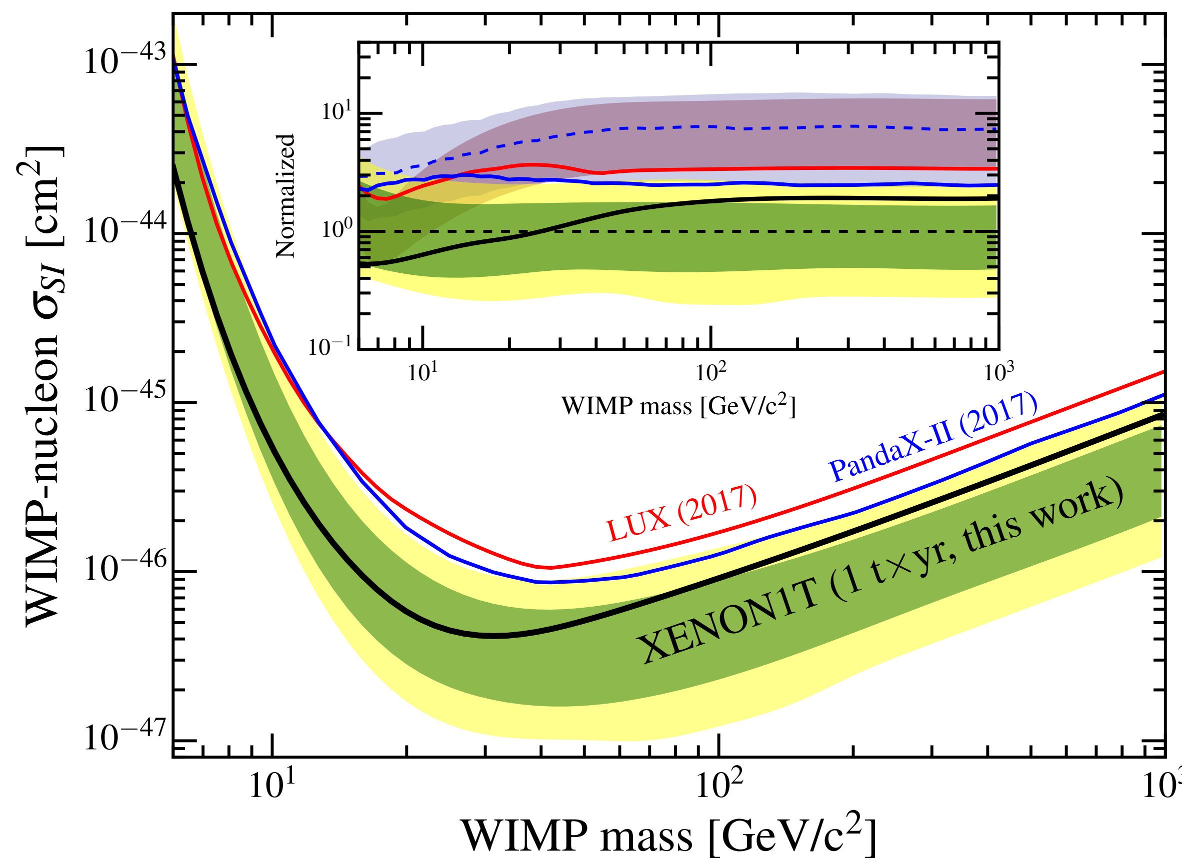
XENON1T comes close to the floor

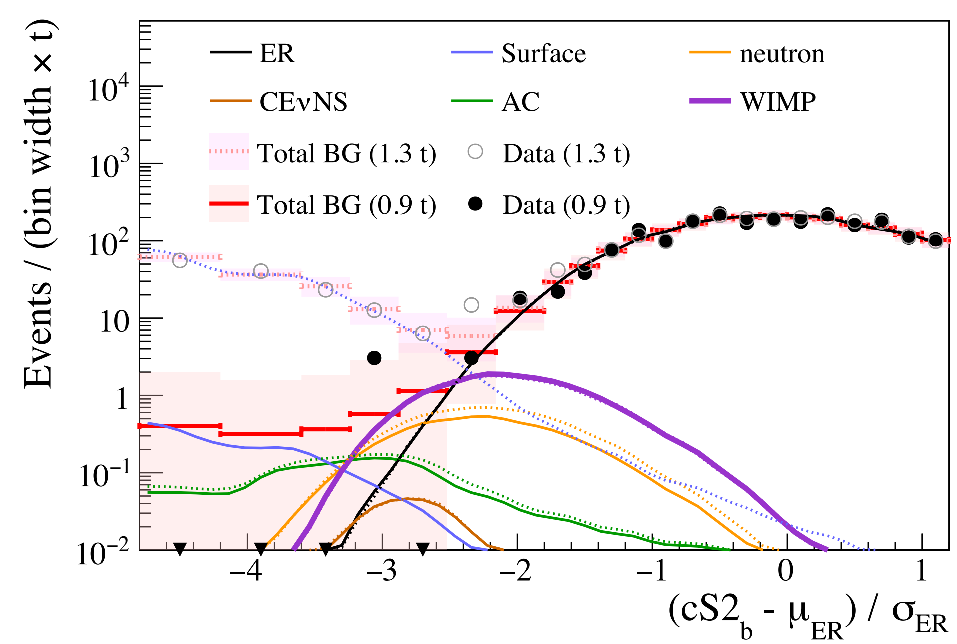
1805.12562

90cm



r=45 cm





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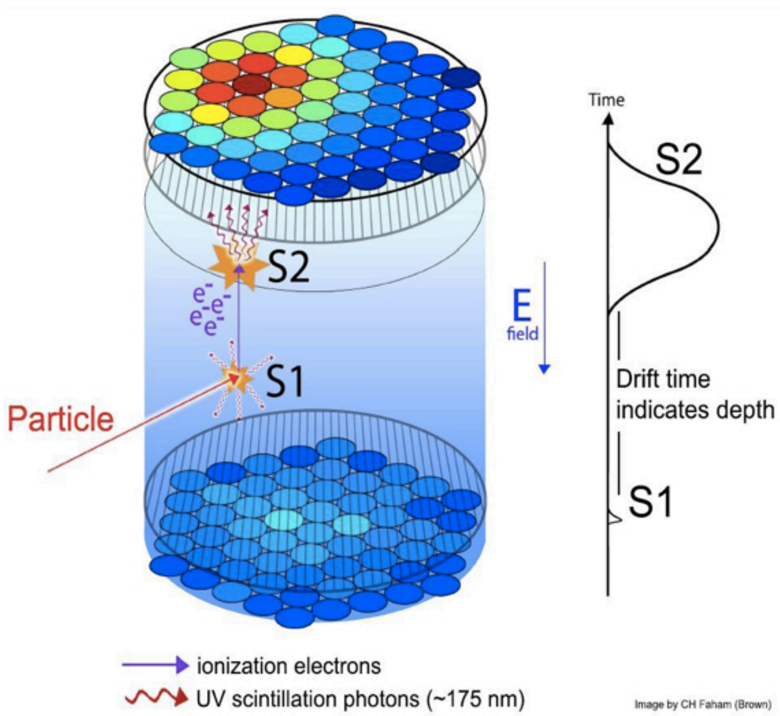
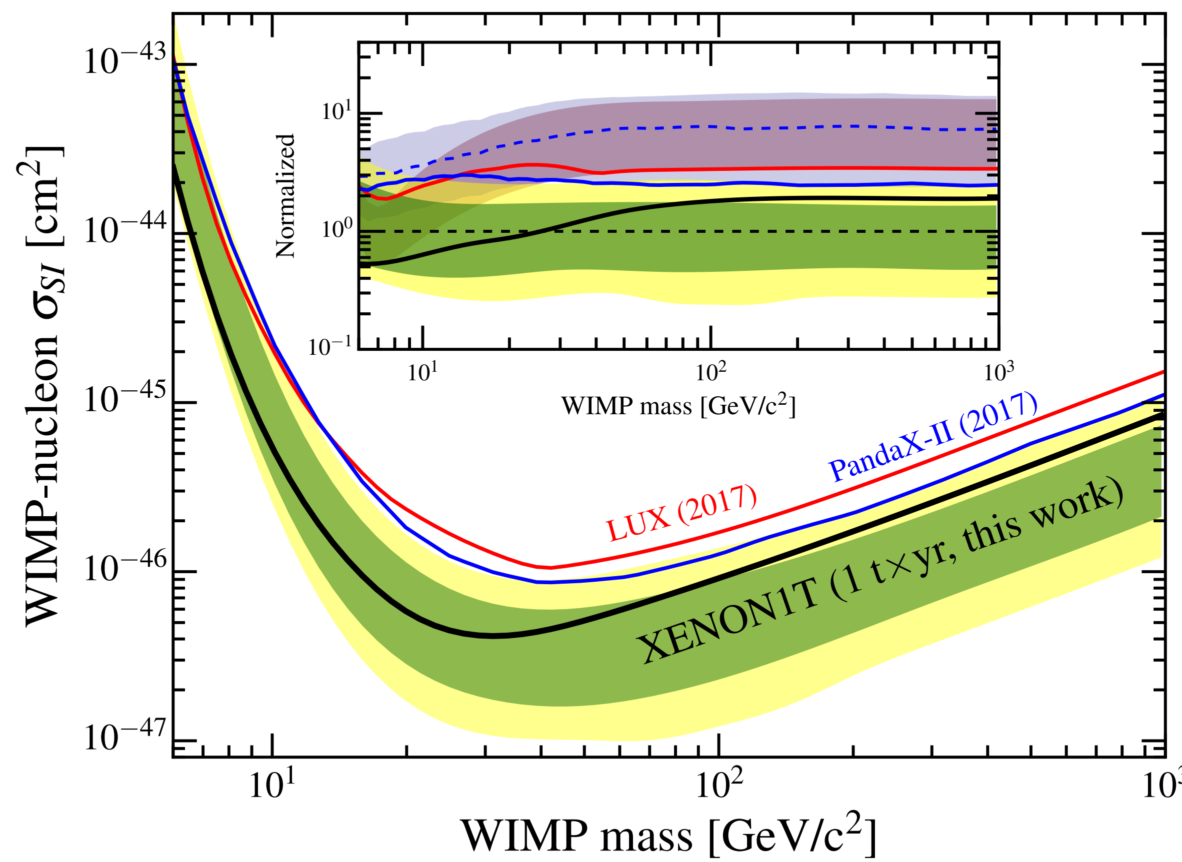
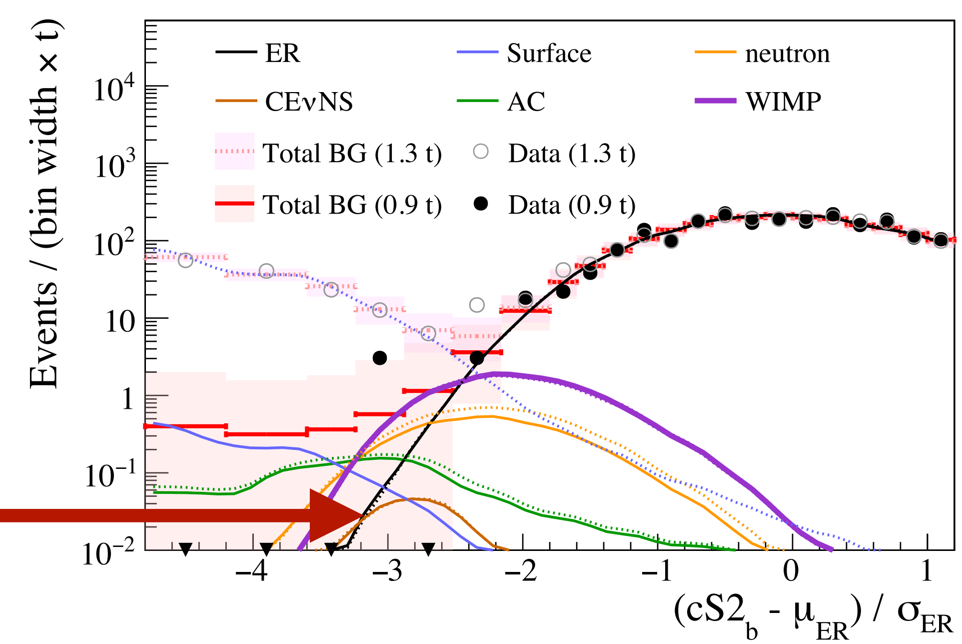


r=45 cm





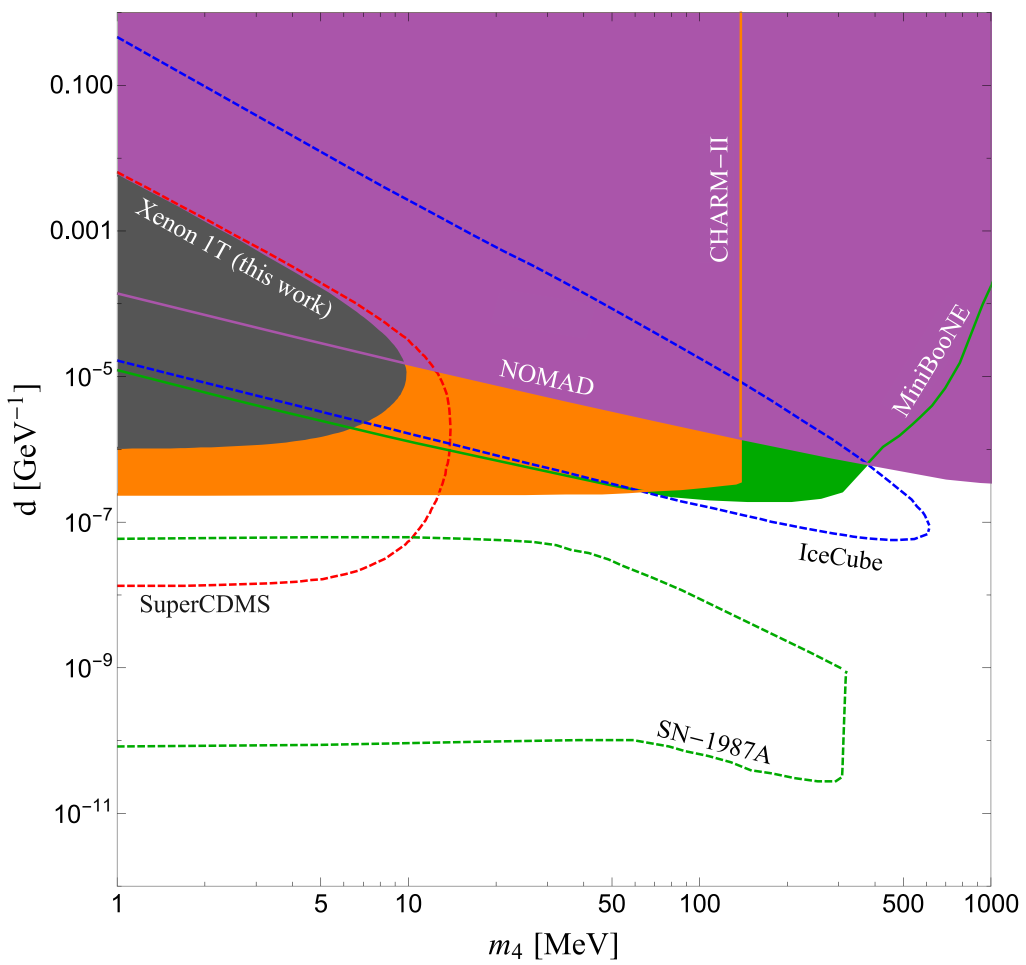
Coherent Elastic Neutrino-Nucleus Scattering ~0.02 events

Direct Detection Experiments at the Neutrino Dipole Portal Frontier

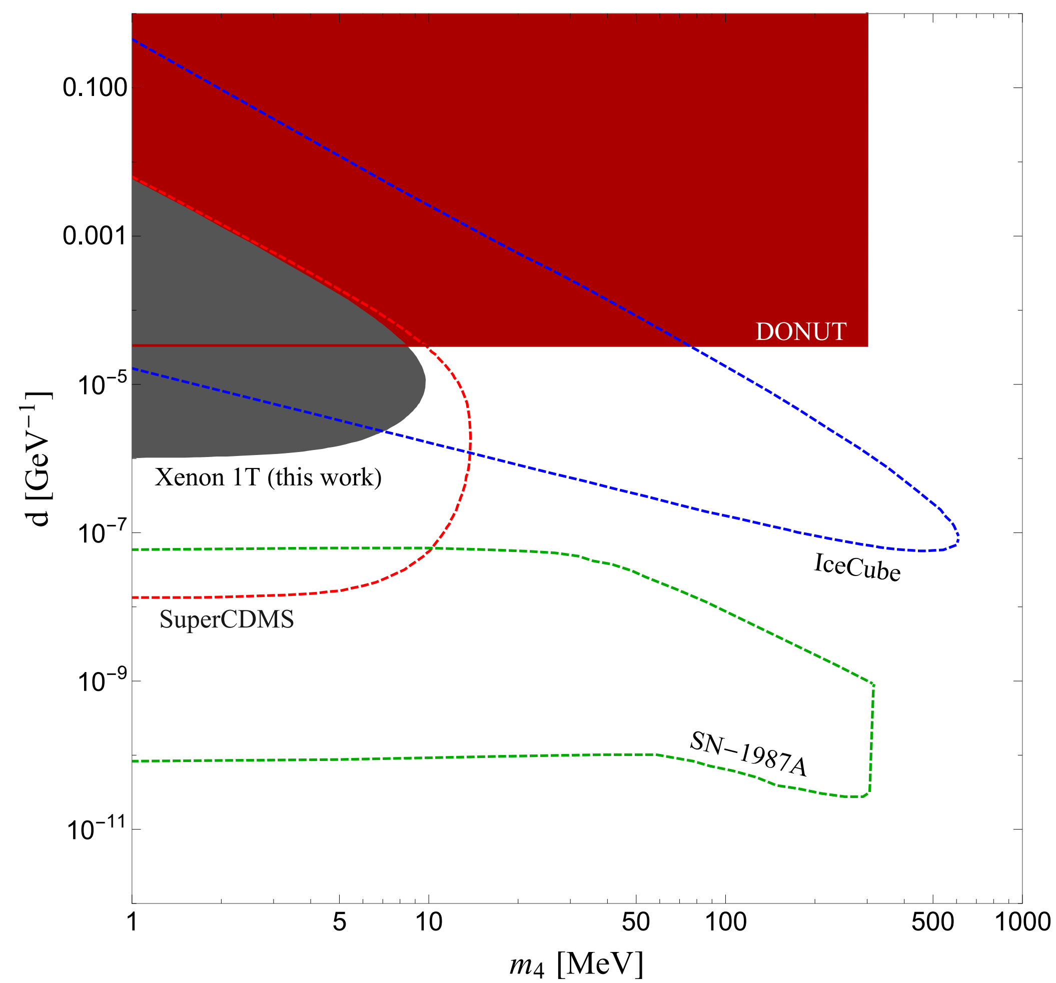
IMS, Wyenberg (PRD 2019)

$$\mathscr{L}_{\text{NDP}} \supset d\left(\bar{\nu}_L \sigma_{\mu\nu} F^{\mu\nu} N\right)$$

mu-flavored



tau-flavored



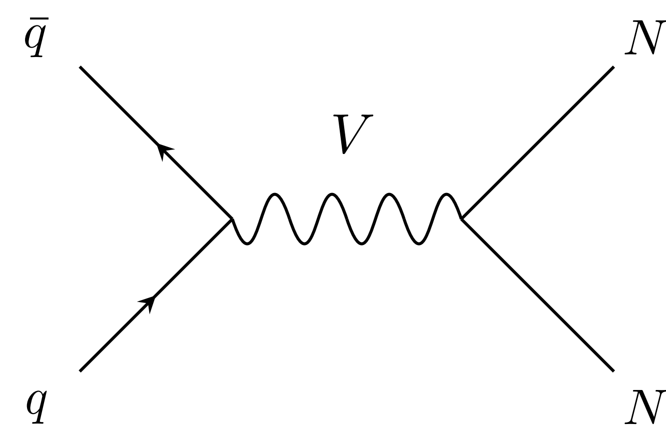
- **Current XENON1T data improves bounds more than order of magnitude at low masses in tau case.**
- **Future data can close gap down to the SN1987A limit (Magill, Plestid, Pospelov, Tsai, [1803.03262]) for both muon/tau.**

Shedding Light on Neutrino Masses with Dark Forces

Batell, Pospelov, Shuve [1604.06099]

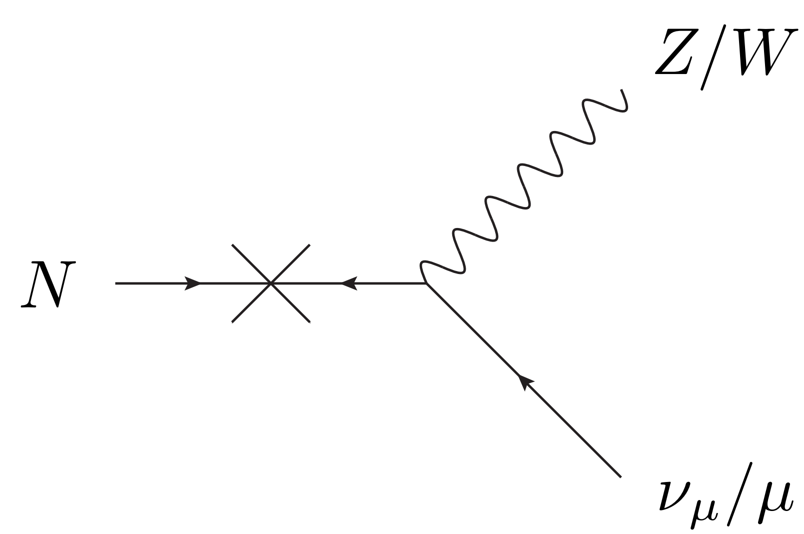
Think globally/act locally: $U(1)_{B-L}$

Make it from new gauge force



$\sim g_{B-L}^2$

break it from EW force



$\sim U$

Scenarios with non-EW decay rates too?

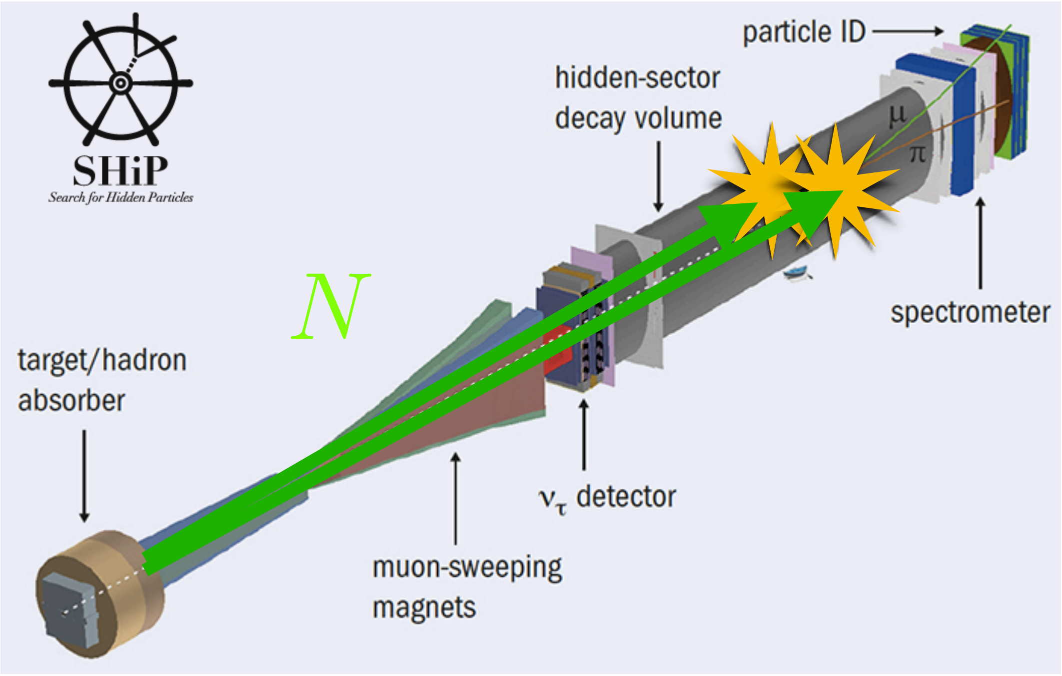
Seesaw Tests at SHiP

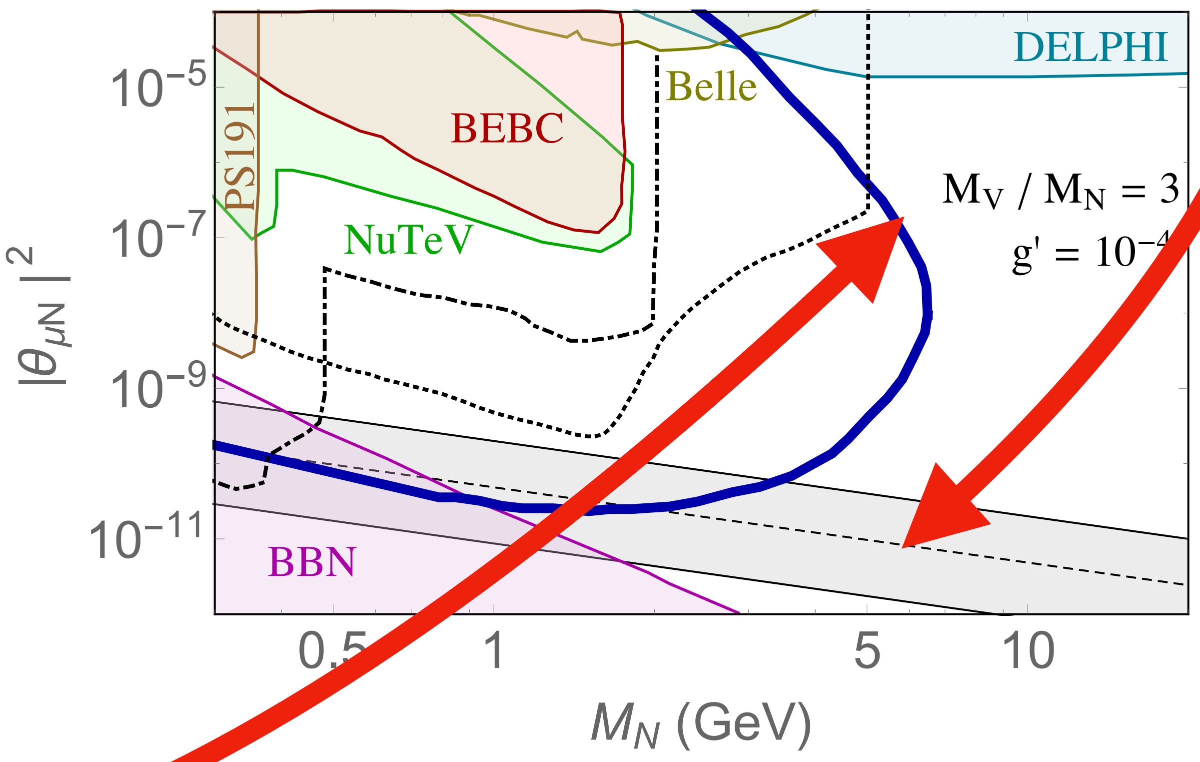
Seesaw relations:

$$m_\nu \approx \frac{M_D^2}{M_N}, \qquad \theta^2 \approx \frac{m_\nu}{M_N}$$
$$M \approx M_N,$$

$$\theta^2_{s-s} \sim 5 \times 10^{-11} \times \left(\frac{1\ \text{GeV}}{M_N}\right)$$

Fix gauge boson coupling/mass





SHiP

Sterile Neutrino Interactions in the Early Universe

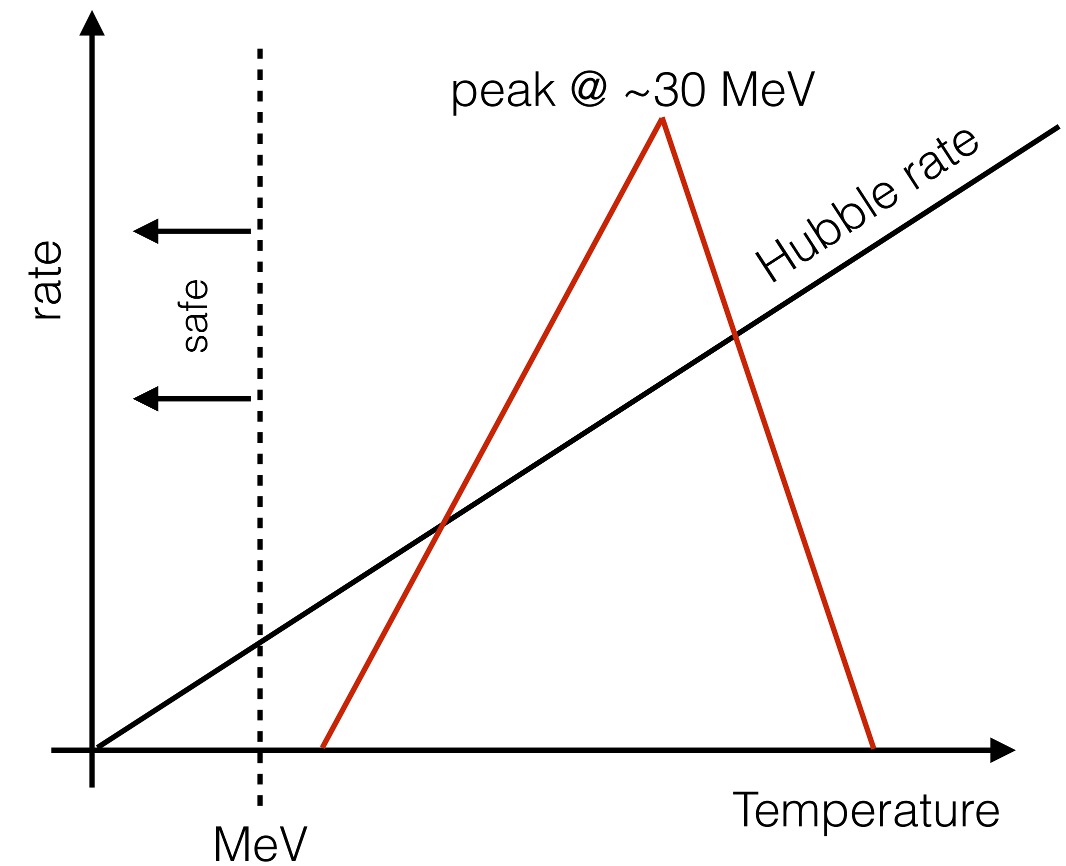
Cartoon of Truly Sterile Neutrinos in the Early Universe

recoupling = Oscillations + Collisions

- SM active neutrinos decouple at ~ MeV from rest of plasma.
- If the sterile neutrino is in equilibrium with the bath before then, and they fully equilibrate, then we have N_{eff} = 4.

@ low-T:
oscillations >> collisions

$$G_F^2 T^2 \times T^3 \times \frac{1}{2}\sin^2 2\theta_{as}$$



@ high-T:
collisions >> oscillations

Flavor build up is interrupted frequently

$$P(\nu_a \to \nu_s) \sim \sin^2 2\theta \left(\frac{\Delta m^2}{T\Gamma_{EW}}\right)^2$$

$$\Gamma_{fc} \sim P(\nu_a \to \nu_s)\Gamma_{EW}$$

$$\sim \sin^2 2\theta (\Delta m^2)^2 G_F^{-2} T^{-7}$$

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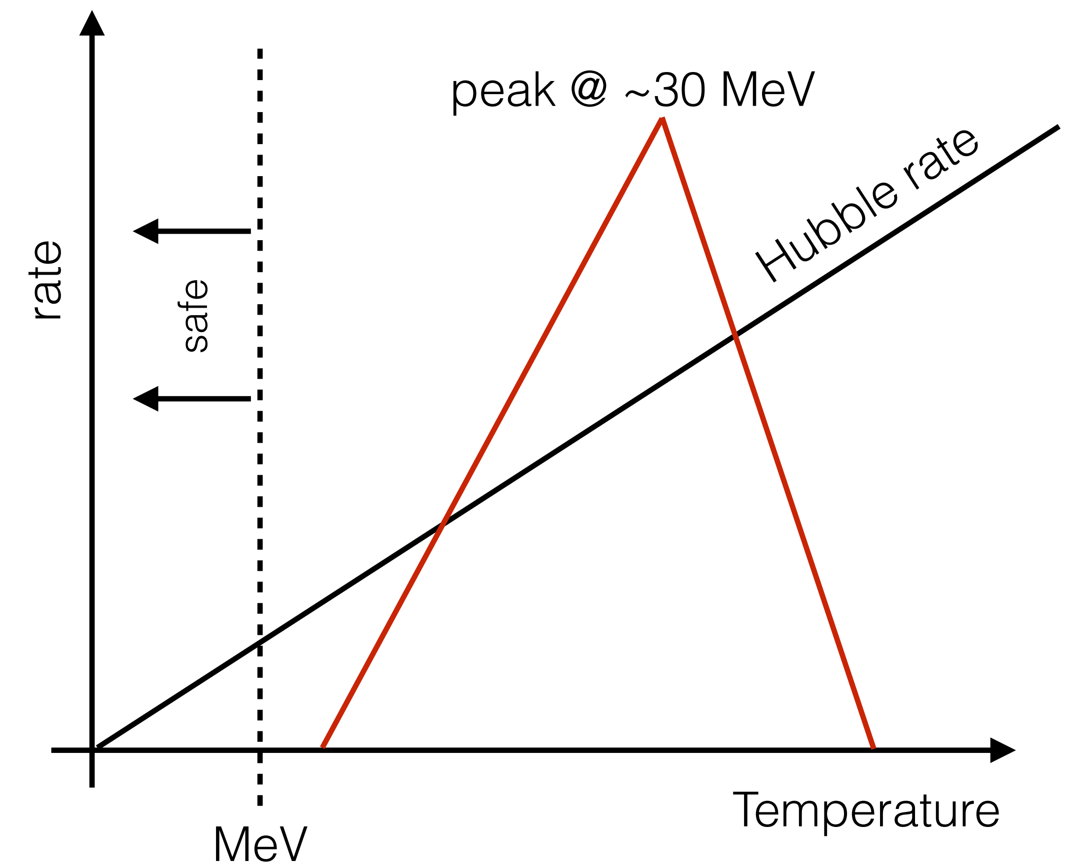

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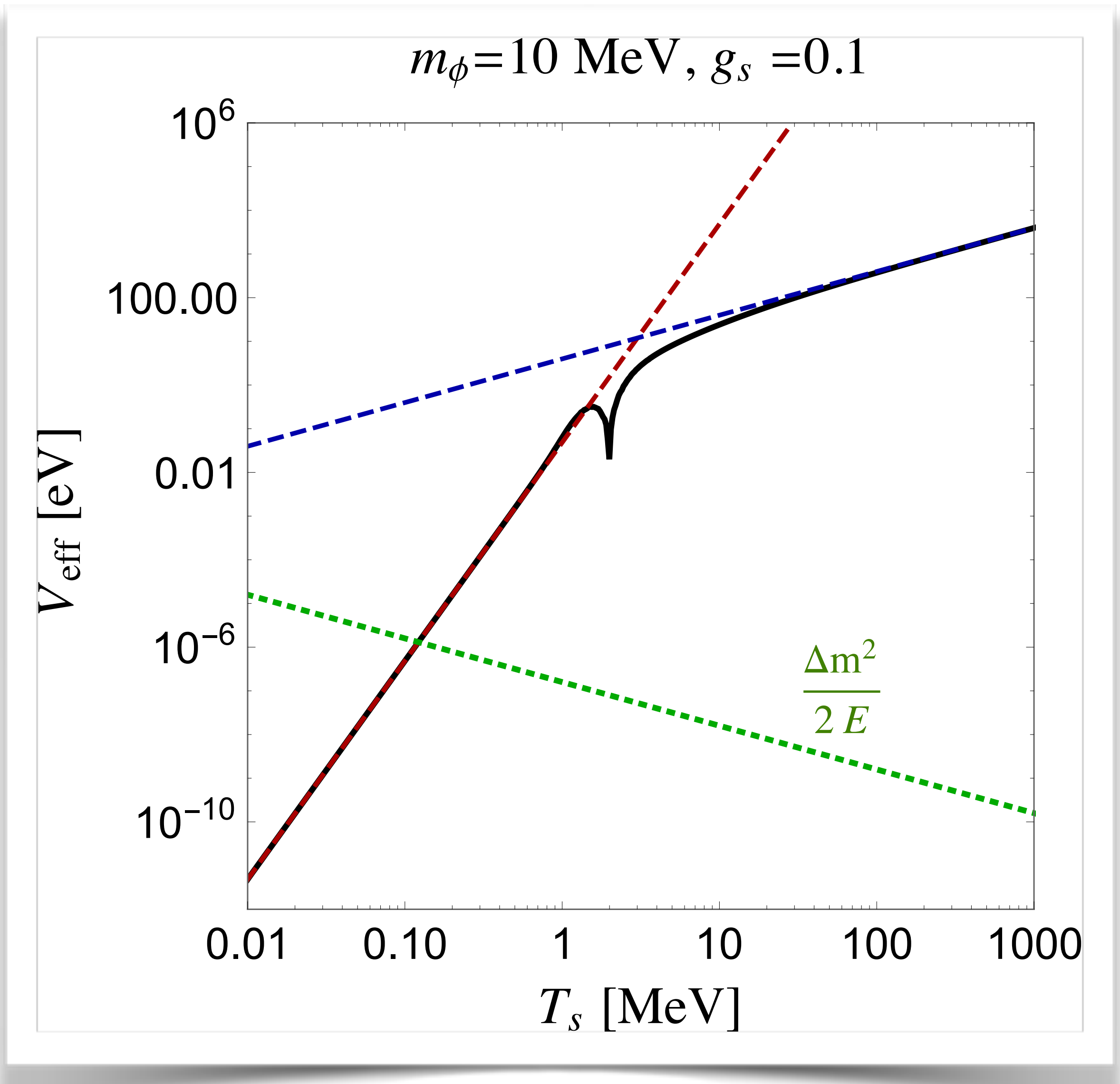
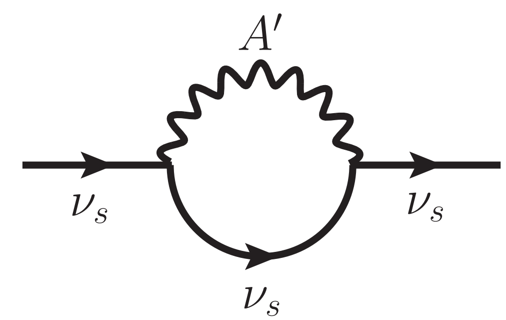
*Doesn't look good for **truly** sterile neutrinos.*

An interacting neutrino loophole

- In medium mixing angle modified as: $$\sin^2 2\theta_{\rm M} = \frac{\sin 2\theta_0}{\left(\cos 2\theta + \frac{2E_s V_{\rm eff}}{\Delta m^2}\right)^2 + (\sin 2\theta)^2}$$
    - Suppress the mixing angle with a new term in the MSW potential.

Babu, Rothstein, (1992); B. Dasgupta, J. Kopp (2014); S. Hannestad, R. S. Hansen, and T. Tram, (2014);





- Strong suppression when $$V_{\rm eff} \gg \frac{\Delta m^2}{2E}$$

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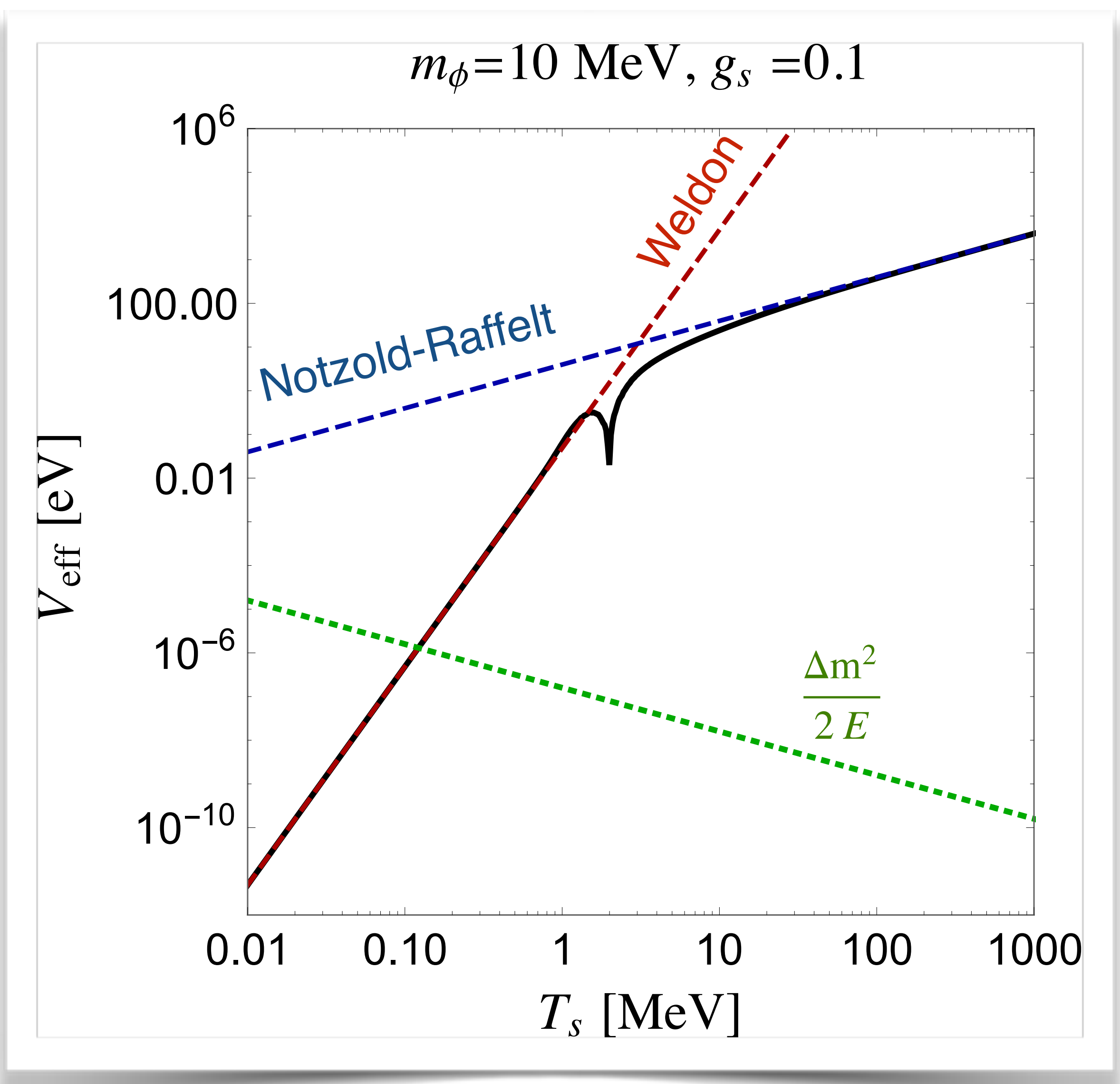
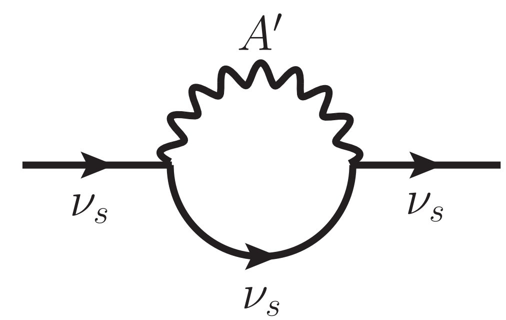




- Strong suppression when

$$V_{\rm eff} \gg \frac{\Delta m^2}{2E}$$

- Basic estimates done >25 years ago:

$$V_{\rm eff} \simeq \begin{cases} -\frac{7\pi^2 g_s^2 E_s T_s^4}{45 m_\phi^4}, & \text{if } E_s, T_s \ll m_\phi \\ \frac{g_s^2 T_s^2}{8E_s}, & \text{if } E_s, T_s \gg m_\phi. \end{cases}$$

Notzold Raffelt (1988)

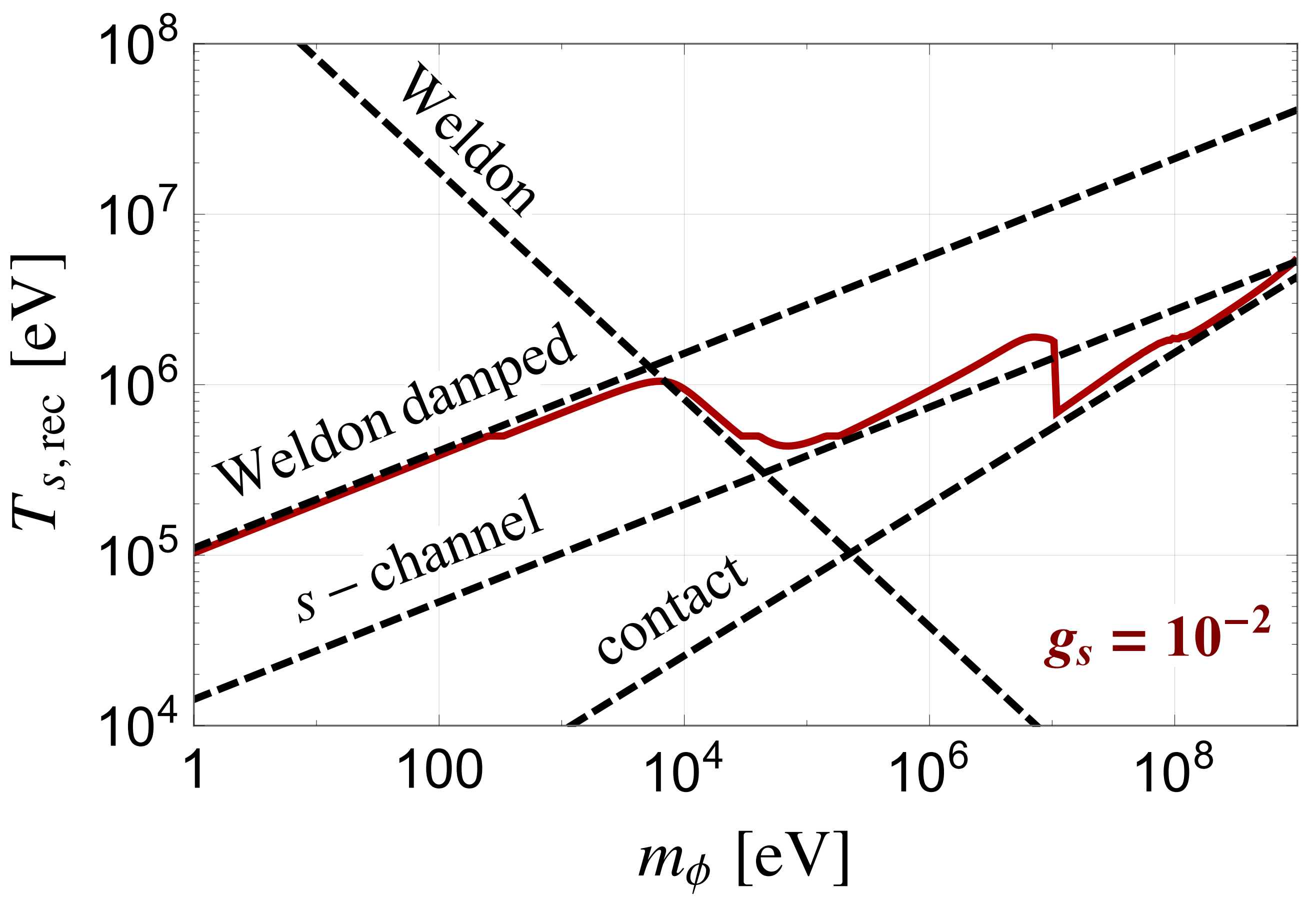
Weldon (1982)

Collisions Matter

Cherry, Friedland, IMS [1605.06506]

$$\nu_a \nu_s \to 2\nu_s$$

$$H(T_{rec}) \sim \Gamma(T_{rec})$$



- Numerical evolution following Stodolsky (red curve).
  - Good agreement with analytic estimates.
- A few windows with sub-MeV recoupling, in line with CMB constraints.
- Works down to coupling

$$g_s \simeq 10^{-6}$$

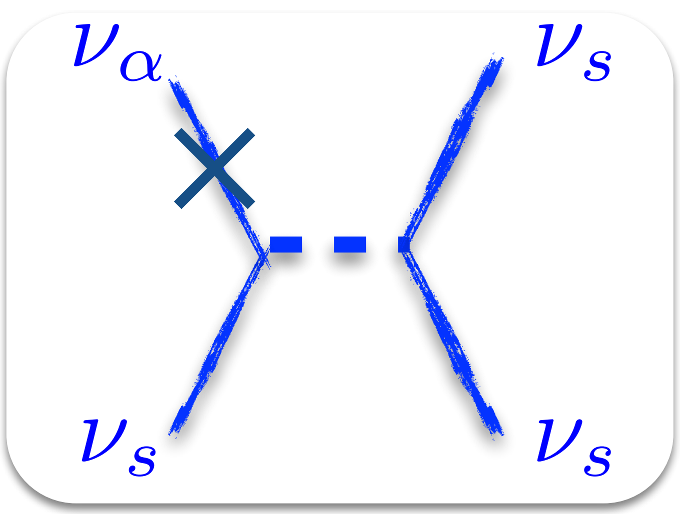
below which, mixing angle suppression turns off.

Back to Antarctica…

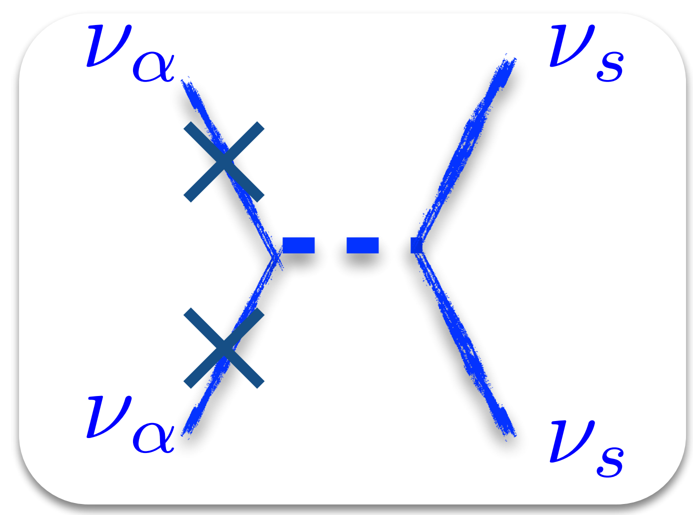
Effect on IceCube Data

ν_α source flux scatters is sterilized by scattering ~ essentially disappears.

$$2 m_\nu E_\nu = m_\phi^2$$



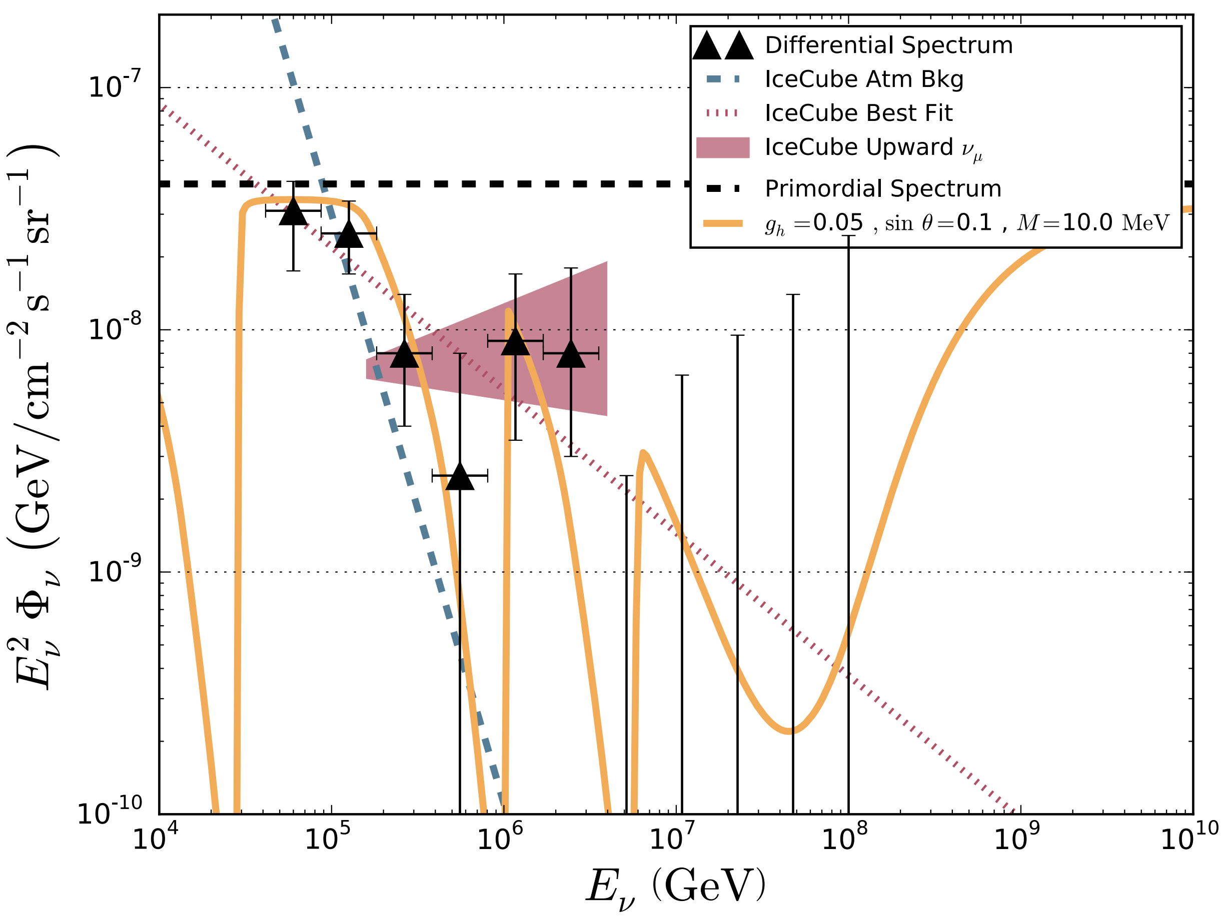
Heavy CνB particle
= Lower resonance energy



Light CνB particle
= Higher resonance energy

Example spectrum

4 absorption features, but sterile feature behind bkg.



Resonant absorption at:

$$E_\nu = \frac{m_\phi^2}{2m_{\nu_i}}$$

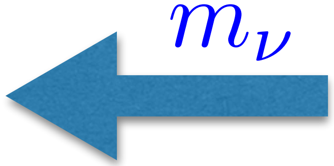
Cherry, Friedland, IMS [1605.06506]

Example spectrum

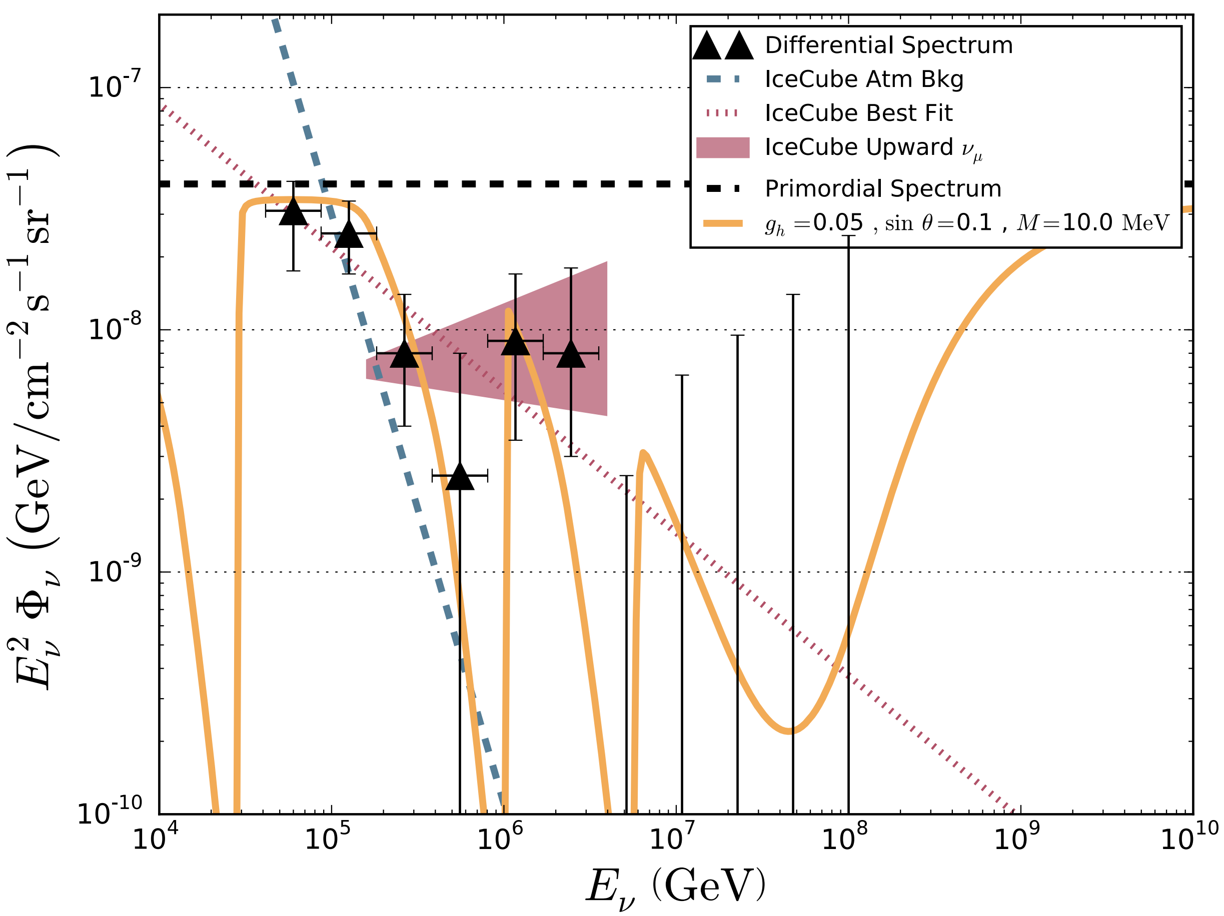
4 absorption features, but sterile feature behind bkg.

increase

m_ν



absorption moves to low-E



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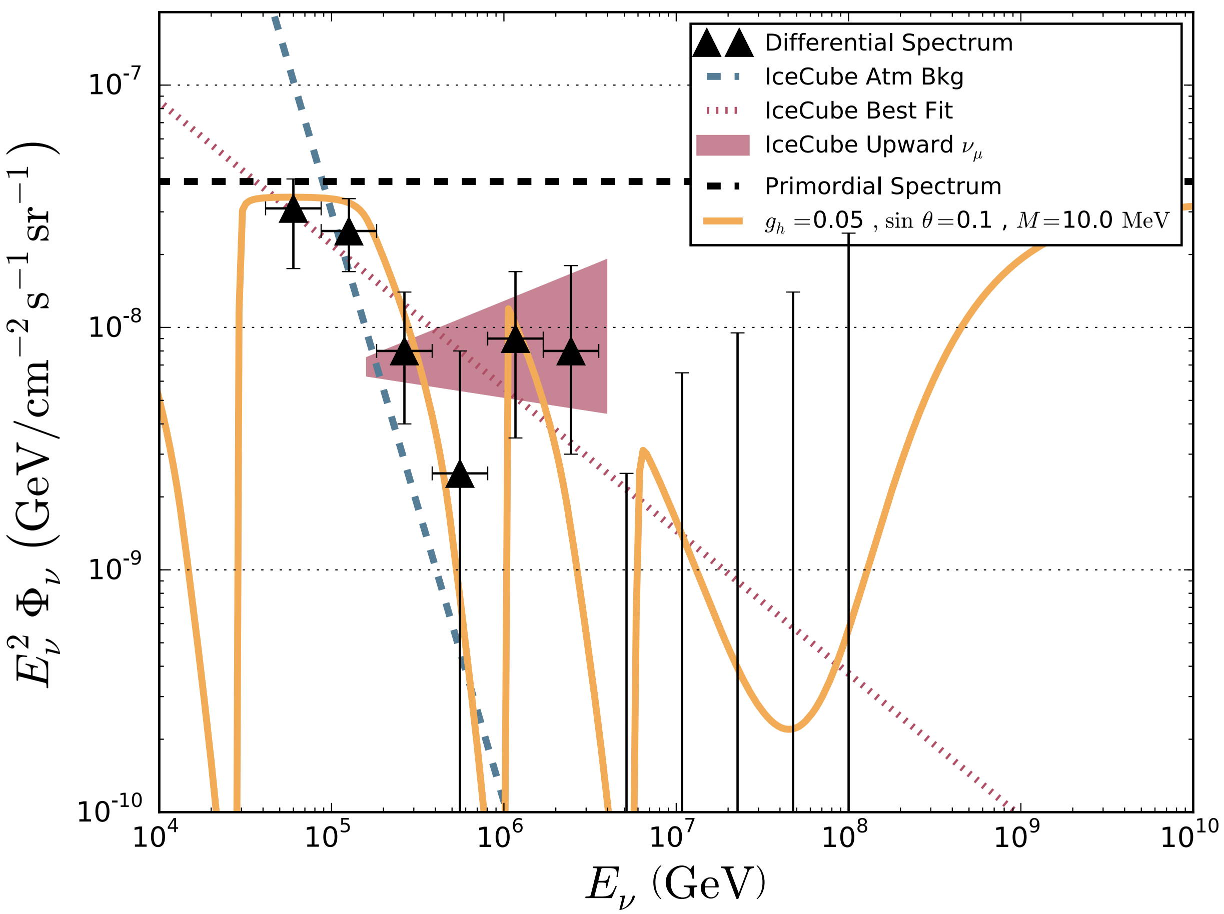

Resonant absorption at:

$$E_\nu = \frac{m_\phi^2}{2m_{\nu_i}}$$

Cherry, Friedland, IMS [1605.06506]

increase m_ϕ

absorption move to high-E

Conclusions

- Sterile neutrinos are totally reasonable ingredients of BSM theories.
    - But we don't know how many, how heavy, or if they connect to a larger sector.
- Wide ranging phenomenology:
    - **Truly sterile neutrinos**:
        - Can play the role of Dark Matter if at **keV** scale.
        - Produce novel double-bang events at IceCube at **GeV** scale.
    - **New but not-sterile neutrinos**:
        - **MeV** states at direct detection experiments & double bang events for **GeV** states.
        - **eV** scale self-interacting neutrinos can be consistent with cosmology, while producing novel "dips" in flux at IceCube.
        - Impacts of sterile neutrino DM + new interactions → See upcoming talks by Sen and Johns.